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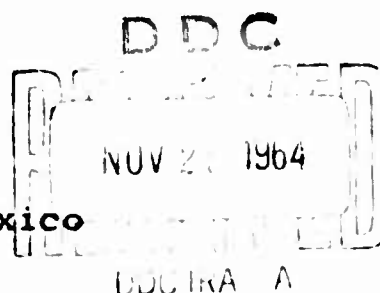
**AN EXPERIMENTAL DETERMINATION OF ULTRASONIC WAVE  
VELOCITIES IN PLASTICS AS FUNCTIONS OF TEMPERATURE**

**By  
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**A Thesis  
Submitted in Partial Fulfillment of the  
Requirements for the Degree of  
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## TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS .....	111
LIST OF FIGURES .....	iv
 CHAPTER	
1. Introduction .....	1
2. Literature Review .....	4
3. Experimental Methods .....	15
4. Experimental Results .....	36
5. Summary .....	54
APPENDIX A. Longitudinal Wave Velocity in Solids ...	56
APPENDIX B. Sample Identification .....	59
APPENDIX C. Experimental Data on Heating of Samples..	63
APPENDIX D. Drawings of Bonding Clamp .....	69
APPENDIX E. Maximum Error Calculations .....	72
APPENDIX F. Velocity Data for Nose Cone Materials ..	81
LIST OF REFERENCES .....	92

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## LIST OF FIGURES

Figure		Page
1.	Acoustic portion of apparatus used by Nolle and Sieck .....	10
2.	Typical acoustic apparatus for differential path method .....	11
3.	Two acoustic assemblies, different only in sample thicknesses .....	18
4.	Bonding clamp .....	21
5.	Bonding clamp with acoustic unit in place .....	21
6.	Block diagram of measuring circuit .....	25
7.	Schematic representation illustrating interpolation time-measuring technique .....	29
8.	Longitudinal wave velocity in nylon .....	40
9.	Longitudinal wave velocity in low density polyethylene .....	42
10.	Longitudinal wave velocity in Plexiglas .....	43
11.	Longitudinal wave velocity in high density polyethylene .....	43
12.	Longitudinal wave velocity in Teflon .....	45
C-1.	Sketches of samples used in study of sample heating .....	64
C-2.	Internal temperatures of Plexiglas sample .....	66
C-3.	Internal temperatures of polyethylene sample ..	67

Figure	Page
D-1. Drawings of bonding clamp .....	70
D-2. Parts list for bonding clamp .....	71
F-1. Longitudinal wave velocities in CNP and C124	83
F-2. Velocity in TWNP .....	84
F-3. Longitudinal wave velocities in Avcoat I and 19 .....	85
F-4. Longitudinal wave velocity in Avco FG .....	89
F-5. Longitudinal wave velocity in GEFG .....	89

## CHAPTER 1. INTRODUCTION

This thesis reports the results of an experimental investigation into the effects of temperature on the velocity of ultrasonic longitudinal acoustic waves through various plastics. This investigation was undertaken at the suggestion of Dr. Arthur H. Guenther, of the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, and the experimental work was accomplished in the Physics Branch of that laboratory. There were two principle reasons for the Weapons Laboratory's interest in ultrasonic wave velocities.

First, and more important, another research project currently in progress at the laboratory required data on acoustic wave velocities through heated plastic materials. These materials included special-purpose plastics used in the nose cones of ballistic re-entry vehicles for which there was no published data. In the absence of information concerning the effects of temperature changes on acoustic wave velocities, it was necessary to assume the velocities to be independent of temperature, even though it was known that this assumption was incorrect.

Secondly, it was desired to have available for future use in the laboratory an established method of measuring ultrasonic velocities. Such measurements could be utilized to aid in distinguishing between similar materials and to determine acoustic impedances. Additionally, such measurements would provide the laboratory with a means of checking the uniformity of materials supplied by contractors.

Thus, the study covered by this thesis was undertaken for very specific reasons: to determine needed data that was not available elsewhere and to establish a facility for measuring ultrasonic velocities.

Before proceeding further, a word on definitions is in order. The term "ultrasonic" is now commonly used to describe vibrational waves having frequencies higher than those normally audible to the ear, i.e., any acoustic wave of a frequency higher than approximately 20 kc is said to be ultrasonic. In some older works the word "supersonic" was used to mean the same thing, but such usage is no longer sanctioned by convention. Similarly, "ultrasonics" is defined as "the technology of sound at frequencies above the audio range," and "supersonics" is now defined to be "the general subject covering phenomena associated with speed higher than the speed of sound (as in



the case of aircraft and projectiles ...)." (1)<sup>1</sup> This study is concerned only with "ultrasonics." The remainder of the thesis is divided into four major chapters.

Chapter 2 presents the results of a survey of the literature undertaken to study previously used methods of measuring ultrasonic velocities and to provide the necessary background knowledge.

In Chapter 3, the experimental methods used in this study are described. The chapter includes a discussion of the factors that influenced the choice of methods.

Included in Chapter 4 are the velocity-temperature data for five common plastics and a discussion of experimental errors.

A brief summary of the results of the investigation is given in Chapter 5.

Additional details on selected topics are included in Appendixes A through E. Appendix F contains velocity data pertaining to several nose cone materials. This information was released for publication in an unclassified report after completion of the text of the thesis.

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<sup>1</sup>Footnotes in this report are indicated by superscript Arabic numerals. References are cited by an Arabic numeral in parentheses, the number agreeing with the number of the specific entry in the List of References following the appendixes.

## CHAPTER 2. LITERATURE REVIEW

The reader interested in acquiring background knowledge for a study of the relatively modern technology of ultrasonics might logically turn first to the parent science, acoustics. Such a reader would do well to acquire a copy of Lord Rayleigh's Theory of Sound.<sup>(2)</sup> In addition to Rayleigh's classic work, the cited reference also contains an excellent historical introduction by Lindsay.<sup>2</sup> In his introduction, Professor Lindsay describes the contributions to acoustics of such people as Pythagoras, Aristotle, Galileo, Boyle, Poisson, Helmholtz, and a host of other great names of science whose works preceeded those of Rayleigh.

With the legitimacy of acoustics thus well established, the reader can then turn to more modern works for a specific introduction to the high frequency offspring of classical acoustics known as ultrasonics.

Among the better textbooks for this purpose are those of Carlin (3), Crawford (4), Mason (5,6), and Hueter and Bolt (7).

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<sup>2</sup>Robert Bruce Lindsay, the author of this introduction is, himself, an eminent physicist and contributor to the literature of acoustics and mechanics.

Excellent review articles have been written by Hearmon (8), Huntington (9), and McSkimin (10).

The particular problem of concern in this study was the determination of longitudinal wave velocities in solids. Many people have worked in this field, and the literature abounds with descriptions of the various methods that have been used. In the following paragraphs several of the more important methods are briefly described, and references to the original works are cited.

As might naturally be expected, some of the early work in ultrasonics was done at the lower ultrasonic frequencies and employed extensions of techniques that had been used for frequencies in the audible range. In 1925, Quimby (11) determined the velocities of longitudinal waves in bars of aluminum, copper, and plate glass by determining resonance frequencies. He used a quartz crystal to piezoelectrically excite vibrations in the bars and determined the resonance frequencies by employing a small disk delicately suspended at a  $45^\circ$  angle adjacent to the free end of the bar. Vibrations in the bar caused waves in the adjoining air which, in turn, caused the disk to rotate on the quartz fiber from which it was suspended. Quimby measured the torque needed to restore the disk to its original position, the maximum torque being

needed when the bar was vibrating at a resonance frequency. The basic disk apparatus had been described many years earlier by Rayleigh (2) for application at low sonic frequencies.

In an article published in 1932, Debye and Sears (12) noted that ultrasonic waves in a liquid or transparent solid cause alternate layers of compression and rarefaction which effectively constitute a diffraction grating for light which is passed through the medium supporting the acoustic vibrations. Debye and Sears worked with various liquids, and they employed frequencies of 1.7 Mc, 5.7 Mc, and 16.5 Mc. Their measurements of velocity were made by measuring the angles at which Bragg reflections occurred, which gave the wavelength of the acoustic vibrations. The velocity of propagation was computed as the product of wavelength and frequency. Willard (13) gives a comprehensive discussion of this and other optical methods which have been used for velocity measurements. His article includes descriptions of wave interference methods which can be applied to opaque as well as to transparent solids.

The previously described methods were among those which utilize continuous, or sustained, acoustic waves. At the higher ultrasonic frequencies it has been more common to use pulsed wave techniques. Some of the more frequently used pulse methods are described below.

Probably the most simple and direct method of measuring velocity or speed is that used to determine automobile or aircraft speed records, i.e., direct measurement of the time required to cover a known distance. Many ultrasonic velocity determinations have been made by direct measurement of the elapsed time required for an ultrasonic pulse to traverse a known distance through a sample of the material being studied. Direct time measurements have been made in a variety of ways with many different experimental configurations.

One basic type of experimental arrangement based on direct time measurement is the liquid immersion technique, of which two variations have been reported.

In one of these, a single piezoelectric transducer is used both as a transmitter and as a receiver of ultrasonic pulses. Such an arrangement was described by Nolle and Mowry (14). Using frequencies in the range between 10 and 30 Mc with pulses of approximately 2  $\mu$ sec duration, these workers measured the time required for an echo to return to the transducer after a round trip of a known distance through a liquid medium (either water or ethanol). They then inserted between the transducer and the reflecting surface a thin sample of the solid material being studied and again measured the elapsed time from the sending of a pulse until its echo was received. The velocity of the wave through the sample was

computed from the knowledge of sample thickness and the difference in echo time with and without the sample in the path of transmission.

Basically the same arrangement was used in another variation of the liquid immersion technique reported by Ivey, Mrowca, and Guth (15). The main difference was that these workers used two transducers, one as a transmitter and the other as a receiver. They measured the elapsed times for pulses to traverse a known distance through the liquid between the transducers. They made such measurements both with and without samples in the path of the transmission in order to determine the transit time through the sample. This method has the advantage that less acoustic energy is lost to reflections than in the case where echo times are measured in the single-transducer technique.

Probably the most frequently used technique is one in which a single transducer is attached either directly to the sample or to a buffer rod which, in turn, is attached to the sample. Buffer rods, or transmission blocks as they are also called, are commonly made of quartz, fused silica, or of a metal such as aluminum, and they are used to convey acoustic waves into the samples being studied. In this technique, the velocity is determined by measuring the time between subsequent echoes of a transmitted pulse as if it is reflected

back and forth between parallel faces of the sample.

Obviously, this method is best suited for use with low-loss materials so that the echoes are strong enough to be easily detected after suffering energy losses due to reflections and multiple passages through the material.

An early example of this technique is in the work done by Huntington (16) in determining the elastic constants of crystals. As explained by Huntington and others (17), the elastic constants of certain crystals can be calculated from a knowledge of longitudinal and transverse wave velocities through the crystals. Indeed, much of the work that has been done in ultrasonics has been done for the purpose of determining such physical constants. Other examples of this method are given by Lazarus (18) and by Eros and Reitz (19).

As might be expected by analogy to the liquid-immersion examples previously discussed, another variation of the solid-buffer technique is one in which two transducers are used to measure the transit time for a one-way trip through the sample rather than measuring echo times for round trips. Nolle and Sieck (20) used this method to measure velocities through a synthetic rubber. Without going into details as to the cements and bonding agents used, the method used by Nolle and Sieck was basically as follows: They placed their rubber samples between

two aluminum transmission blocks and placed quartz crystal transducers at the two extreme ends of the acoustic assembly as shown in Figure 1.

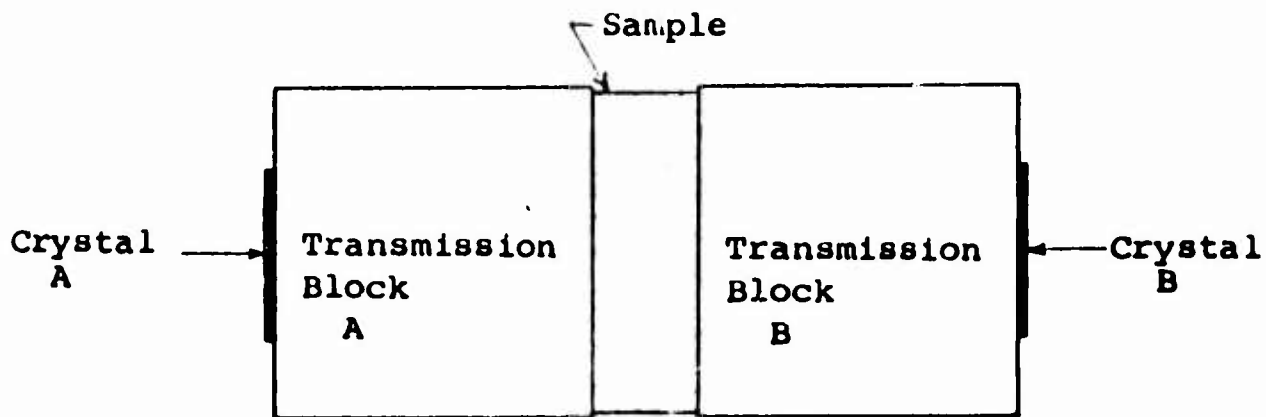


Fig. 1. -- Acoustic portion of apparatus used by Nolle and Sieck.

In making their determinations of wave velocities, these workers measured the transit time for a pulse to pass through the complete assembly from A to B. They also measured the time for an echo to return to the transducer after reflection from the sample interface. They did this for each of the blocks by transmitting, in turn, from each of the crystals. They then subtracted the average of the block transmission-times from the total transit time to obtain the time required for an ultrasonic pulse to traverse the sample.



Another direct time measurement technique is based on measuring the times required for pulses to traverse two paths of different lengths. This is a single transducer method and depends on the use of an acoustic assembly such as that shown in Figure 2. A shoulder or notch is machined into a bar of the sample material so that two reflecting surfaces are provided.

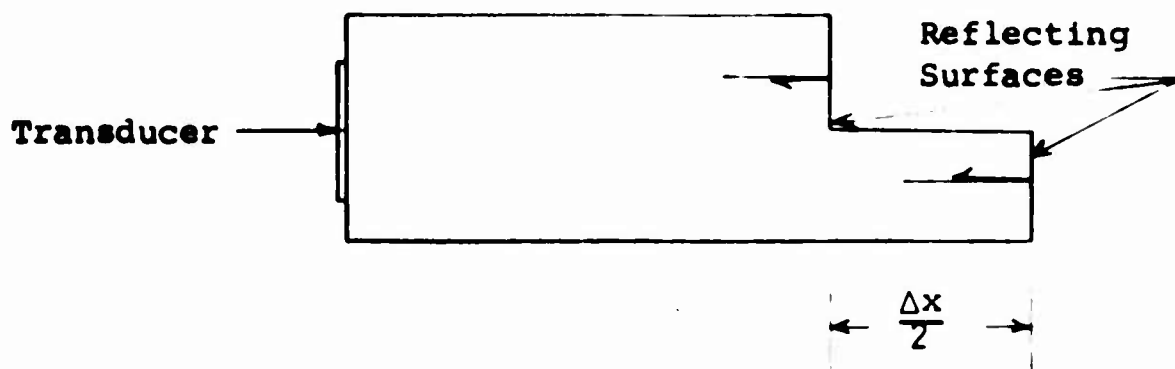


Fig. 2. -- Typical acoustical apparatus for differential path method .

The velocity is computed by dividing the difference in path lengths by the difference between the echo times received from the two reflecting surfaces. This method is useful with low-loss materials at very high temperatures since the notched end of the bar can be placed in an oven at temperatures which would damage the transducer. The differential path method has been used by Frederick (21), by Bell (22), and by Krause (23).

While direct time measurements are simple and straightforward, they do not provide extremely accurate velocity determinations. This is particularly true in the case of very small samples where the proportional error can be quite large. McSkimin (24) has written an article discussing the problems involved in working with small samples. In this article, special attention is given to the details of experimental techniques.

Various methods have been contrived to provide greater accuracy than that attainable by timing methods. Holbrook (25) has reported on the "sing-around" method which is particularly useful in making accurate determinations of small changes in velocity such as those due to small changes in temperature. In this method, separate sending and receiving transducers are used. The received signal is amplified, detected, and sent back to the oscillator to trigger the next pulse. Changes in velocity then show up as changes in the pulse repetition frequency and are easily determined. Absolute velocities can also be determined after careful evaluation of all the electrical delays in the measuring circuitry.

A high degree of accuracy can be achieved by the use of phase comparison methods such as those reported by McSkimin (26). He describes precise means of comparing the phase relations between waves transmitted directly through a sample and those

that have passed through the sample twice because of reflections at the surfaces of the sample. McSkimin gives both exact and approximate expressions for the wave velocity through the material. The same author also discusses this phase comparison method in another article (27) dealing primarily with low temperature studies. With the proper equipment and careful work, errors due to phase comparison need not exceed one part in 10,000 according to McSkimin (26).

Another application of a phase comparison method is illustrated by Merkulov (28) in describing a Russian-developed velocity-measuring instrument that uses a "... phase method of making two radio pulses coincide. One of the pulses traverses the specimen to be tested (placed between two metal bars) and the other is passed through a reference liquid delay line with the precisely known value of velocity." The author states further that, "... the relative precision of the measurement is 0.1-0.3 per cent."

Still another method due to McSkimin is the pulse superposition technique (29). This method provides for the indirect determination of the round trip delay time required for a pulse to traverse a sample cemented to the end of a silica buffer rod. The method is fairly complicated, and a brief description would not do it justice. The reader who is

interested may consult the original literature. McSkimin reports good accuracy and states that agreement with values obtained by phase comparison methods was within one part in 5,000.

While by no means all-inclusive, the list of methods described in this chapter includes the more important and more frequently used means of measuring ultrasonic velocities. Additional methods are described or referred to in the general references cited at the beginning of this chapter (3-10). The techniques used in this study are described in the next chapter.

### CHAPTER 3. EXPERIMENTAL METHODS

The previous chapter showed the abundance of workable methods of measuring ultrasonic velocities which have been presented in the literature. The foremost problem for the investigator was to determine which of the methods was best adaptable to obtaining the desired objectives. There were several factors which affected this determination.

First of all, the time available for the study was limited. This limitation required that the study should be accomplished using equipment which was already available without losing time waiting for new equipment to be delivered.

Another consideration, and one of prime importance, was with regard to the anticipated application of the data expected to accrue from the study. While this consideration cannot be discussed at length in an unclassified report, it may be said that the frequency range of interest was in the low megacycle region. Furthermore, there was no need for extremely accurate velocity determinations. Because of the nature of the other figures with which the velocity data would be used, a relative uncertainty of 5% in the velocity was permissible. Since several of the materials to be studied were obviously inhomogeneous and anisotropic, it was also apparent that any great

precision in determining the velocity of waves through a particular sample would be wasted, in that the results could not be expected to apply with the same precision to some other sample of the same material.

Finally, it was very desirable to have the selected method be simple in concept and easy to apply so that it could readily be used by laboratory personnel after a minimum of instruction.

Fortunately, there were available for immediate use certain items of equipment specifically designed for use in ultrasonic studies.<sup>3</sup> Among these were an Arenberg<sup>4</sup> Model PG-650C pulsed oscillator (along with the coils needed for operation over the frequency range of 0.2-162 Mc) and some Arenberg precision attenuators, capable of providing from 1-122 db of attenuation in 1 db increments. There were no transducers for producing ultrasonic vibrations, but this deficiency was soon remedied.

An anonymous benefactor contributed several piezoelectric ceramic transducers. All of these transducers were circular disks designed to vibrate in the thickness mode, i.e., so as

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<sup>3</sup> The availability of this equipment was, indeed, one of the major considerations in the selection of the topic for this thesis.

<sup>4</sup> Arenberg Ultrasonic Laboratory, Inc., Boston, Massachusetts.

to produce longitudinal vibrations. These transducers were nominally 0.030 in. thick and were known to be composed of three different lead zirconate/titanate mixtures. Some were marked to indicate a composition of "65/35 mole % lead zirconate/lead titanate," another group was marked "56/44 ....," and the third group was described as "52/48 % lead zirconate/lead titanate." No further information was available as to the past histories of the transducers. The 56/44 and 52/48 transducers were plated on both faces with a metallic coating. Both faces of each of the 65/35 transducers had been painted with a conductive silver paint.

Other more general laboratory items, such as oscilloscopes, time-mark generators, and various temperature controlling devices were also available for use in this study. There was a well-equipped machine shop capable of providing any shop support which might be needed.

An appraisal of the resources at hand and a consideration of the other determining factors discussed above indicated that a direct timing method should be employed. The three essential parts of a timing apparatus, consisting of (a) an electronic system for generating pulses of sinusoidal oscillations of the desired frequencies, (b) transducers to convert the electrical pulses into ultrasonic pulses (and vice versa), and (c) appropriate display and timing devices, were on hand

and ready for use. This method is both simple and direct, and the precision electronic equipment which was available made it possible to anticipate overall accuracy well within the limits required in the application of the data.

To eliminate complicating considerations such as transducer and circuitry delay times, it was decided to base the determination of velocity on measurement of the time required for pulses to traverse samples of different thicknesses. This is best explained by reference to Fig. 3.

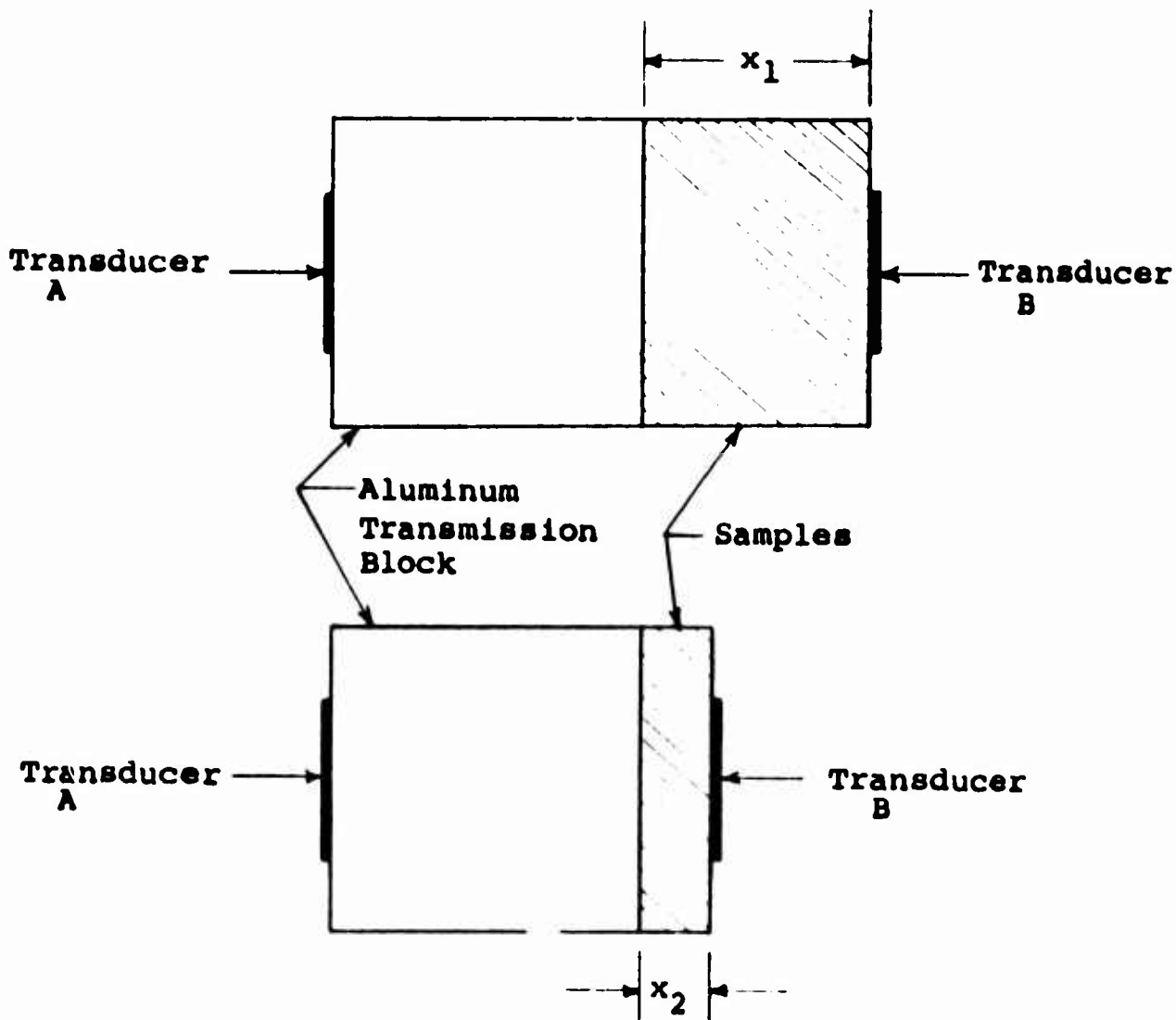


Fig. 3. -- Two acoustic assemblies, different only in sample thicknesses.



Let the transit time from A to B with the thick sample in place be  $t_1$ , and the transit time from A to B with the thin sample in the acoustic unit be  $t_2$ . Then the velocity of the pulse through the sample material can be calculated as

$$v = \frac{\Delta x}{\Delta t} = \frac{x_1 - x_2}{t_1 - t_2}.$$

If the same aluminum block<sup>5</sup> and the same transducers are used while making the measurements of  $t_1$  and  $t_2$ , then the transducer delay times and the transit time through the aluminum need not be determined since these constant delays disappear on computing the difference in times,  $t_1 - t_2$ . This method, of course, assumes that the acoustic units can be reproducibly assembled and that the difference in transit times is due only to the difference in sample thicknesses. It was therefore necessary to devise some means of achieving uniformity and reproducibility in putting together the various parts of the acoustic units.

In an effort to obtain more accurate and reproducible ultrasonic measurements, Sullivan (30), working at the Watertown Arsenal Laboratories, developed a bonding clamp which gave good results. Sullivan's clamp was designed for use with a single transducer method rather than the double

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<sup>5</sup> The function of the aluminum block is to make the overall transit time greater than the duration of the ultrasonic pulse so that the transmitted and received signals are well separated in time.

transducer technique chosen for this study.<sup>6</sup> A variation of the same basic type of clamp, modified to permit the use of two transducers, was designed and constructed for use in the experimental work of this investigation. Photographs of the resulting device are shown in Figs. 4, 5. Detailed drawings of the clamp are included in Appendix D.

The transmission blocks were cut from 2 in. diameter round bar stock of 2024 aluminum alloy. The ends of the rods were machined to make them flat and parallel, and then they were polished smooth. The rods used in this work were of the following lengths:  $3/4$  in., 1 in., and 2 in. Most of the measurements were made using a single  $3/4$  in. transmission rod as shown in Fig. 5. In certain cases the samples were placed between two transmission rods for measurement.<sup>7</sup>

The samples were, for the most part, also cut as right circular cylinders of approximately 2 in. diameter. The exact shape of the sample is immaterial, provided the dimensions are large enough so that the approximation of assuming an infinite medium is valid. This assumption is discussed in

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<sup>6</sup>The double transducer method was chosen to permit the use of thicker samples and to provide greater sensitivity, especially at elevated temperatures where most plastics are highly attenuating ultrasonic media.

<sup>7</sup>This was the practice followed in the case of plastics which softened appreciably at elevated temperatures. It was also used in an alternate velocity measuring scheme to be described later.

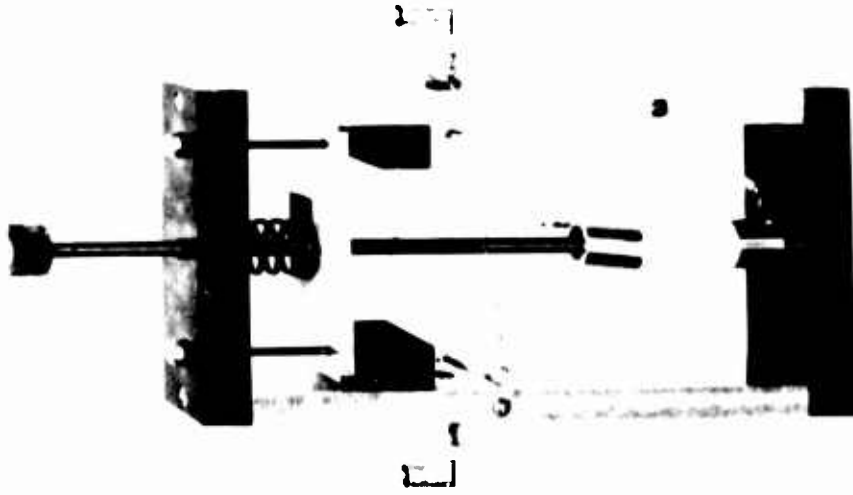


Fig. 4 -- Bonding Clamp

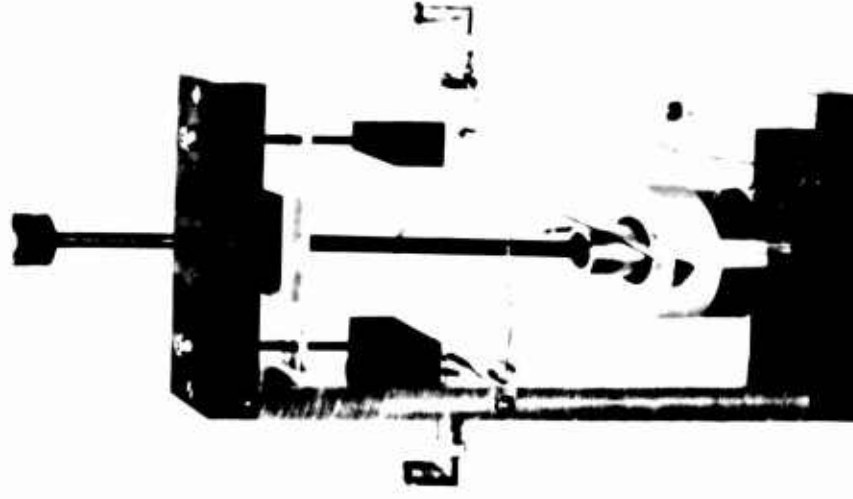


Fig. 5 -- Bonding clamp with acoustic unit in place.

Appendix A. It is imperative that the two active faces of the samples are flat, parallel, and smooth. This quality was achieved with varying degrees of success. The most uniform samples were obtained by a milling process, with the samples held in the mill by means of a vacuum chuck. More details on the individual samples are given in Appendix B.

On assembling the acoustic units a light transformer oil<sup>8</sup> was used as a coupling agent between the various components to increase the amount of acoustic energy transmitted from one material into the next.<sup>9</sup> The selection of this particular bonding material was based on a fortunate combination of circumstances.

First, as Carlin (3) reports, light transformer oil is one of the better and more commonly used couplants. Secondly, it is a nonconducting liquid suitable for use in a constant temperature bath. Finally, a thermostatically controlled bath and a supply of transformer oil were available for use in this work. The natural result of this combination of circumstances was the decision to achieve temperature control by means of an oil bath and to use the same oil as the acoustic coupling agent. By using the same oil for both purposes there was eliminated any

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<sup>8</sup>"Special Marcol 42-46," produced by Humble Oil and Refining Company.

<sup>9</sup>Carlin (3) and Sullivan (30), among others, discuss some of the considerations involved in the coupling of transducers to sample materials.

possibility of problems due to mixture or interaction of two different agents around the edges of the coupled surfaces.

Reference to the drawings<sup>10</sup> and photographs<sup>11</sup> of the bonding clamp will show how it achieves its purpose of aligning and holding the constituent parts of the acoustic assembly in a fixed and reproducible relationship to each other during the velocity measurement procedure. Because of the fact that the clamp's aluminum electrodes are mounted on ball joints, the flat and parallel faces of the transducers, transmission blocks, and samples insure accurate alignment of the various parts of the acoustic assembly. Once assembled, the acoustic unit is held together under uniform pressure by the clamp's spring.

The electrical connections to the transducers are made through the BNC connectors mounted on the sides of the clamp. A shielded wire connects the center conductor of each of these connectors to one of the cylindrical aluminum electrodes on the clamp. The ground connections are made through the wire "cat-whiskers" attached to the aluminum sides of the clamp. In Fig. 5, the ground connection for the lower transducer is made through the aluminum transmission block. Since the plastic samples are nonconducting, an electrode must be provided for

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<sup>10</sup>Appendix D.

<sup>11</sup>Figs. 4, 5.

the side of the transducer next to the sample. A thin (0.00017 in.) piece of aluminum foil can be seen between the sample and the upper transducer in Fig. 5. The ground connection for that transducer is the wire contact seen pressing on the small piece of foil which, in turn, is in contact with the under surface of the transducer.

The following procedural technique was used in assembling an acoustic unit such as that shown in Fig. 5. One of the transducers was placed on a flat, smooth, absorbent paper. A small glass pipet was used to place a drop of transformer oil on the transducer. Then the aluminum transmission block was centered over the transducer and pressed firmly down on it to seal the two pieces together with a thin liquid film between them. The pipet was again used to place 4 or 5 drops of oil on the upper surface of the aluminum block. The sample was then aligned over the block and pressed down to make a thin oil seal between the block and the sample. Next, a few drops of oil were placed on the upper surface of the sample and the thin piece of foil was floated on the oil. A paper straight edge was used to smooth the foil down on the sample. Careful work at this step gave a very tight, smooth connection between the sample and the foil. Then another drop of oil was put on the center portion of the foil surface and the transducer was pressed down into place. After a visual inspection to insure

accurate alignment of the assembled, sandwich-like acoustic unit, it was carefully centered on the lower electrode of the clamp and held in place while the top electrode was screwed down to make contact with the upper transducer. Alignment was again checked and adjusted if necessary. Finally, the clamp was tightened to give the maximum spring pressure on the acoustic unit.

The acoustic unit was then ready to be incorporated into the measuring circuit, a block diagram of which is shown in Fig. 6.

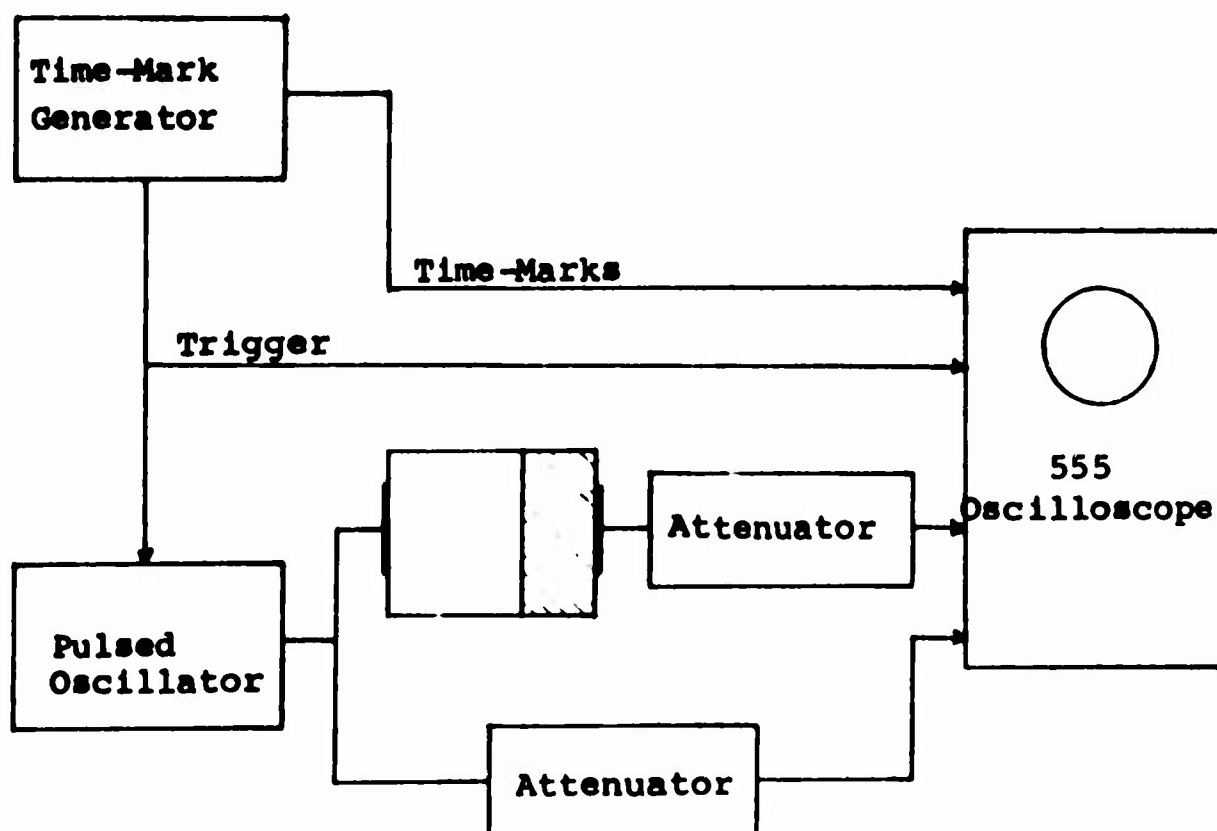


Fig. 6. -- Block diagram of measuring circuit.

The notable feature of this apparatus is its simplicity. A majority of the pulse methods reported in the literature have used a receiver consisting of a detector and an amplifier. In an article previously cited (19), however, Eros and Reitz describe a single-transducer method based on the observation of the unrectified pulses. The latter method was used in the present work. The Arenberg pulsed oscillator used here is rated for an output of up to 600 volts, peak-to-peak. With this strong driving voltage available, it was found that, even for relatively thick samples, the received signal could easily be observed on the oscilloscope without additional amplification. Hence, only the simple configuration shown in Fig. 6 was needed.

In making velocity determinations by a timing method it is necessary to have, on both the transmitted and received pulses, reference points between which the elapsed time can be measured. Therefore the unrectified pulses were observed in their entirety on the oscilloscope so that the time could be measured from one particular oscillation of the transmitted pulse to the corresponding oscillation of the received pulse. During the course of this investigation, several different time-measuring techniques were used.



At first, measurements were made by determining the time from the first positive peak of the transmitted pulse to the first positive peak of the received pulse.<sup>12</sup> However, it was observed that the first one or two oscillations of the received signal were often distorted and of a frequency lower than that of oscillations in the center portion of the pulse. Therefore, there was some doubt as to the accuracy of this method, and it was discarded.

Velocity measurements were next made by using the delayed sweep feature of the Tektronix Type 555 dual beam oscilloscope.<sup>13</sup> By use of the oscilloscope's position and delay controls, the trace of the received signal could be superimposed over that of the transmitted pulse. This permitted careful comparison of the transmitted and received pulses and provided the basis for establishing a relationship between corresponding peaks of the two pulses. The elapsed time could be computed from the graduations on the delay time control potentiometer. (The elapsed time is equal to the

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<sup>12</sup>Because of the polarity of the ceramic transducers, it was necessary to be careful to place them in the acoustic unit in such a way that, if the first peak of the transmitted pulse was positive-going, the first peak of the received pulse was also positive-going. If the first peak of the received pulse was observed to be negative-going, this could be corrected by turning the transducer over so that its other side was against the sample.

<sup>13</sup>Two Type CA dual-trace plug-in units were used so that up to four traces could be observed simultaneously.

amount of time by which the sweep of the receiver channel trace must be delayed in order to cause superposition of the received signal over that of the transmitted signal.) There was some nonlinearity in the delay time circuitry of the oscilloscope so that the potentiometer had to be carefully calibrated over its entire range to give accurate time measurements. Even then, the reproducibility of time measurements was not as good as desired. A refined and self-calibrating technique was developed which gave better results.

In this improved method, ultrasonic pulses of approximately  $3\text{ }\mu\text{sec}$  duration were used. The technique described above was used to superimpose the received and transmitted signals on the oscilloscope in order to identify as reference points two corresponding peaks near the middle of the respective pulses. The transit time was then determined by measuring the delays needed to start the sweeps of expanded oscilloscope presentations at the selected reference points. Fig. 7 illustrates the method.

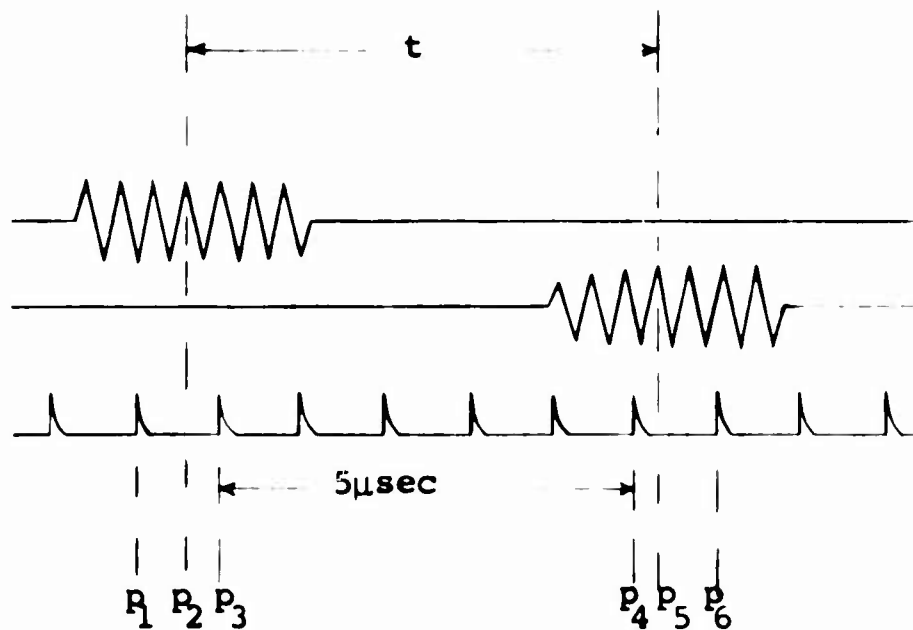


Fig. 7. -- Schematic representation illustrating interpolation time-measuring technique.

The illustration shows three hypothetical oscilloscope traces with a fixed time relationship to each other. They represent, from top to bottom, the transmitted pulse, the received pulse, and a series of  $1\ \mu\text{sec}$  time marks. The desired time interval,  $t$ , is that between the 4th positive peaks of the transmitted and received pulses. Readings of the oscilloscope potentiometer corresponding to the six events marked  $p_1$  through  $p_6$  are recorded, and the elapsed time is computed by assuming that the oscilloscope delay circuit is sufficiently linear over any  $1\ \mu\text{sec}$  interval to permit linear interpolation. The time computation in the hypothetical

example of Fig. 7 is then given by the formula

$$t = \frac{(p_3 - p_2)}{(p_3 - p_1)} + 5 + \frac{(p_5 - p_4)}{(p_6 - p_4)} \quad (\mu\text{sec}).$$

With this time measuring technique, successive measurements using the same acoustic unit regularly agreed to within  $\pm 0.004 \mu\text{sec}$ , and most measurements agreed even closer than that.

In certain cases, the thicker samples of some of the materials studied either caused very high attenuation or excessive distortion of the acoustic waves. This was especially true at elevated temperatures. Under these circumstances, velocity measurements using the technique outlined above became more difficult, and the accuracy came into question. When this happened, the same basic velocity measuring technique as that used by Nolle and Sieck (20), which was previously described in Chapter 2, was used to permit velocity determinations to be made using only one thin sample of the material. This method was used only when necessary, and only if it gave good agreement with the velocity determined by the use of samples of different thicknesses. As used here, the alternate method depended on identification of "corresponding" peaks in the transmitted pulse and in the echoes from the sample interfaces. Because of the phase changes occurring at reflections,

this identification was not always easily made. (Selection of the wrong peak would mean an error of one period in the determination of the transit time through the aluminum transmission blocks.) This alternate method was not used to determine any of the velocities reported in this thesis; it was used with some of the other materials on which a separate report will be issued.

The heart of the time measuring system used here is the time-mark generator. The formula for the computation of elapsed time given in the example above was based on the assumption that the time marks were exactly  $1\text{ }\mu\text{sec}$  apart in time. This assumption was justified by calibration of the time-mark generator<sup>14</sup> by the Kirtland Air Force Base Precision Measuring Equipment Laboratory. The error in the time marks was found to be less than one part per million. The oscilloscope which was used in this work was also calibrated and certified by the same agency.

Since velocities were to be determined as functions of temperature, it was necessary to know something about the heating of the samples and the temperature control provided by the oil bath. Sample temperatures were determined by reading the bath temperatures to the nearest degree by means of a conventional mercury thermometer. The accuracy of the

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<sup>14</sup>Hickok Model 1817 time-mark generator.

thermometer was checked by comparison with another similar thermometer. Also, the thermometer readings were found to agree with the temperatures determined by the thermocouples used in the temperature studies mentioned below. The thermometer was used to measure temperatures at different locations within the oil bath. Repeated observations all indicated that the bath was capable of maintaining uniform temperatures, constant within  $1^{\circ}$  C.

Specific details of the temperature studies are given in Appendix C. Briefly, however, iron-constantan thermocouples were inserted at various locations in the interiors of several different samples to determine the changes in temperature at those points after the samples were inserted in the heated oil bath. The temperatures were then plotted against time to provide a basis for knowing how long it was necessary to wait for internal sample temperatures to be uniform and equal to the bath temperature. The practical result of these temperature measurements was the rule of thumb that the thickest samples used (approximately  $1\frac{1}{2}$  in. thick) should be held at a new temperature for one hour before making any velocity measurements. The thinner samples were allowed somewhat less time for the temperature to stabilize, but in no case was less than one half hour allotted

to the waiting period.

Ultrasonic pulse velocities<sup>15</sup> were measured over the temperature range between room temperature and 100° C. Four different frequencies were used in making the measurements included in this report.

The 0.030 in. thick ceramic transducers originally available could be successfully used over a frequency range from below 1 Mc to higher than 3 Mc. (Their resonance frequency was somewhat less than 3 Mc.) For the sake of convenience, it was decided to operate those transducers at two easily measured frequencies, 1.5 and 3.0 Mc. The selected frequencies were set by using the time-mark generator and the oscilloscope. To obtain an output of 3.0 Mc, e.g., the frequency control of the oscillator was adjusted so that there were exactly three oscillations in any 1  $\mu$ sec interval of the transmitted pulse. By lengthening the pulse, this relation could be checked over an extended interval to insure that there were 3 oscillations in 1  $\mu$ sec, 6 oscillations in 2  $\mu$ sec, ..., 30 oscillations in 10  $\mu$ sec, etc. This technique gave entirely sufficient accuracy and was used to set all the frequencies reported here.

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<sup>15</sup>The velocity referred to here is the bulk velocity, which is the velocity of propagation of longitudinal waves through an unbounded medium. See Appendix A for more details.

In order to permit velocity measurements at higher frequencies than those obtainable with the original transducers, some additional ceramic transducers were purchased. These were of lead zirconate/lead titanate composition equivalent to PZT-5. They were disks of 3/4 in. diameter with resonance frequencies of 5 and 10 Mc.

The 5 Mc transducers were used at the frequency of 4.33 Mc because of the fact that the oscillator could not be adjusted to give a 5 Mc output with those transducers in the circuit. One of the plug-in coils for the oscillator gave a maximum frequency of somewhat less than 5 Mc. Using the coil designed for the next higher frequency range, the lowest frequency obtainable was above 5 Mc. Because of this gap in frequency coverage, 4.33 Mc was selected as the best of the available frequencies at which to drive the 5 Mc transducers. (This frequency was set by adjusting the output so that there were 13 cycles in 3  $\mu$ sec, 26 cycles in 6  $\mu$ sec, etc.)

The measurements made at the frequency of 10.0 Mc were made by using the 10 Mc PZT-5 transducers at their resonance frequency.

Because of the large number of materials studied, there was not time to make measurements at all four frequencies over the entire temperature range. The 5 and 10 Mc transducers



were not received until late in the study. For these reasons, measurements were made using 1.5 and 3.0 Mc waves over the total temperature range covered. After this work was completed, the velocities of 4.33 and 10.0 Mc pulses were measured at room temperature. To the degree of accuracy achieved here, the velocity does not appear to be very dependent on frequency, and it seems safe to assume that the velocity data for the higher frequencies would essentially follow the same curves as those obtained using 1.5 and 3.0 Mc waves.

The velocity measurements made using the principal method (time measurement by interpolation) described in this chapter have proved to be repeatable. During the final part of the study a technician was assigned the task of learning this method of measuring ultrasonic velocities. He made duplicate measurements of several velocities which had previously been determined by the author. The agreement between the values obtained by the two different observers was good, always within 1%.

The temperature dependent velocity data obtained for five common plastics is presented in the next chapter.

## CHAPTER 4. EXPERIMENTAL RESULTS

Some preliminary measurements of ultrasonic velocities through two metals were made to provide a check on the accuracy of velocity measurements using the apparatus and procedure described in the last chapter. The obvious way to make such a check is to measure the velocity through some common materials and compare the results with published values. This was not quite so easy as had been anticipated, however, due to a disparity between the materials that were available for study and the materials for which published velocity data were available. Also, it was noted that handbooks generally do not include the temperatures or frequencies at which reported velocity measurements were made. In spite of these difficulties, sufficient agreement with published data was obtained to demonstrate that the method was capable of giving results well within the range of allowable error (5%). A discussion of the errors inherent in the method will be given after the presentation of the data.

One of the materials used to provide an accuracy check was the 2024 aluminum alloy which was used to make the transmission blocks. A series of ten measurements was made using the superposition timing method described in Chapter 3. The values ranged from a low of 6.34 mm/ $\mu$ sec to a high of 6.47 mm/ $\mu$ sec. The arithmetic mean and the median of the ten values were both 6.40 mm/ $\mu$ sec. These measurements were made at room temperature (27° C) and at a frequency of 3.0 Mc.

The best comparison values found (1) were for "rolled aluminum" (6.42 mm/ $\mu$ sec) and for "Duralumin 17 S" (6.32 mm/ $\mu$ sec), neither of which is exactly the same as the 2024 alloy used.<sup>16</sup>

The velocity of longitudinal waves through a magnesium alloy<sup>17</sup> was measured on three separate occasions. The values obtained were 5.77, 5.79, and 5.76 mm/ $\mu$ sec.<sup>18</sup> The American Institute of Physics Handbook (AIP Handbook) lists a value of 5.77 mm/ $\mu$ sec for "drawn, annealed magnesium." While not conclusive, the agreement obtained with these two metals was, at least, encouraging.

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<sup>16</sup> Composition of 17ST alloy: 95% Al, 4.0% cu, 0.5% Mn, 0.5% Mg. Composition of 2024 (or 24ST) alloy: 93.4%, 4.5% cu, 0.6% Mn, 1.5% Mg.

<sup>17</sup> Marked "Dow Magnesium, QQ-M-311."

<sup>18</sup> These measurements were made using the preferred timing method illustrated by Fig. 7.

The five common plastics for which velocity data are given here are ones which were on hand in the laboratory at the start of the project. They include a nylon, a low density polyethylene, a high density polyethylene, Plexiglas, and Teflon. There is some published velocity information available for certain of these plastics, and it will be given for comparison with the experimental results obtained here. In each of the graphs on the following pages longitudinal velocity is plotted as the ordinate, and temperature is the abscissa.

Most of the velocity determinations were made by measuring the elapsed times through three samples of different lengths,  $x_1$ ,  $x_2$ , and  $x_3$ . If the corresponding transit times are indicated by corresponding subscripts, then three interrelated velocity calculations can be made according to the formulas

$$v_{12} = \frac{x_1 - x_2}{t_1 - t_2}$$

$$v_{13} = \frac{x_1 - x_3}{t_1 - t_3}$$

$$v_{23} = \frac{x_2 - x_3}{t_2 - t_3}$$

Ideally, of course, all three of these should be equal. If, however, an error is made in determining one of the transit times, there will be poor agreement among the three velocity values, and the experimenter is alerted to the fact that an error has been made. Most of the points plotted on the velocity curves represent the arithmetic mean of three velocity values computed as above.

The first material studied over a range of temperatures was the nylon. The low temperature used was  $25^{\circ}$  C, and the high was  $114^{\circ}$  C. The values obtained are plotted in Fig. 8. The frequency used for most of the measurements was 3.0 Mc. These determinations were made at a time during the study in which the superposition method of timing was being used. Later on, a few velocity determinations were made at frequencies of 1.5, 4.33, and 10.0 Mc using the interpolation timing technique. The later values were consistent with the earlier ones, and all of them are plotted on the same graph. The frequency dependent deviation appears to be no greater than the deviation due to experimental error.

The nylon samples used in this work were cut from a 6 in. diameter rod of Poly-Penco nylon (density 1.15 g/cc). The only nylon velocity value found in the literature was

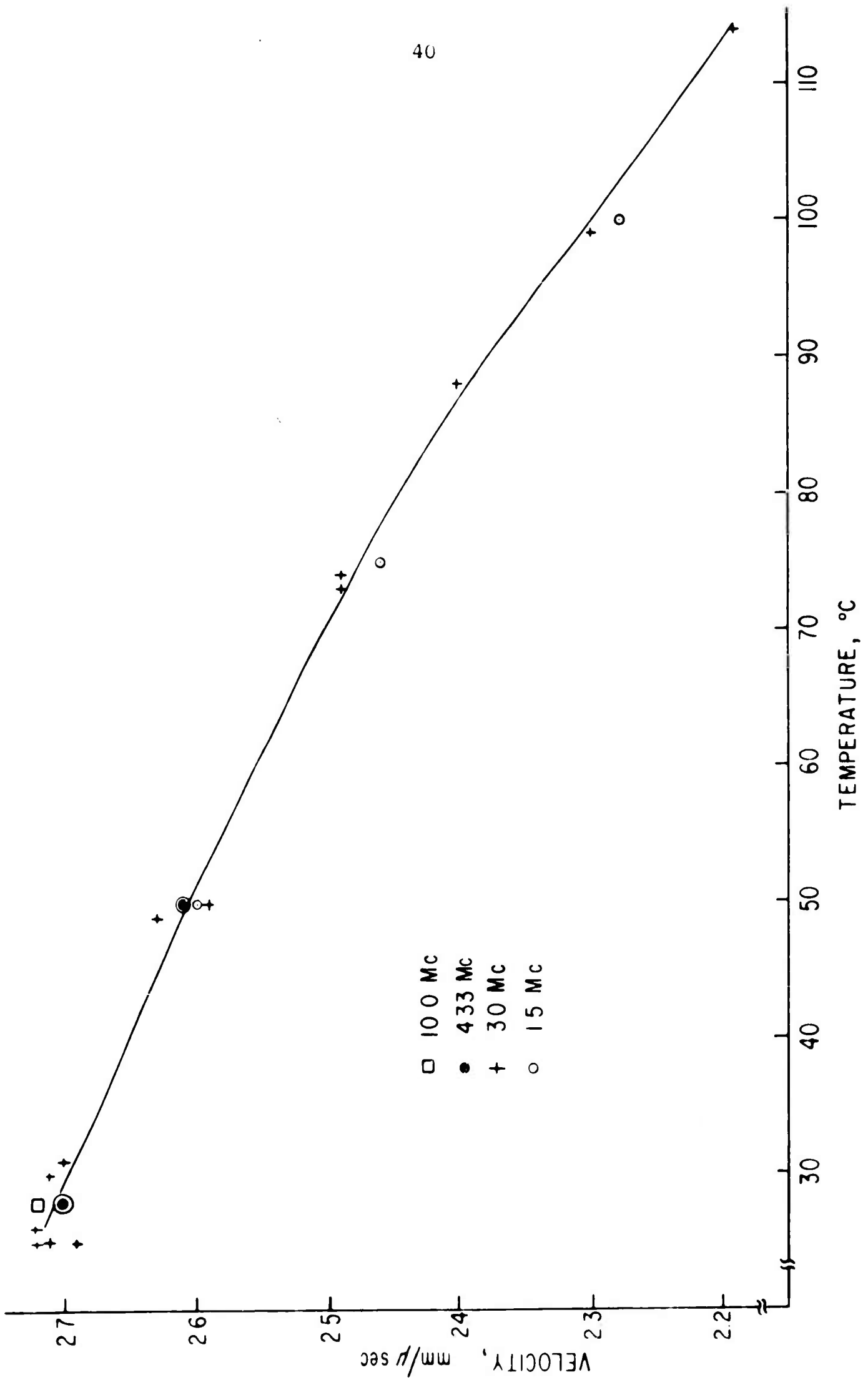


FIGURE 8 LONGITUDINAL WAVE VELOCITY IN NYLON

2.62 mm/ $\mu$ sec (1) for type 6-6 nylon (density 1.11 g/cc) so no valid comparison could be made between experimental and published values.

The next material studied was the low density polyethylene. The velocity data are plotted in Fig. 9. The temperature range used here was necessarily limited to avoid melting or distorting the samples. As in the case of the nylon, a majority of the measurements were made using the superposition method of timing. Again, all values are plotted on the same graph.

The AIP Handbook shows the longitudinal wave velocity in a low density (0.90 g/cc) polyethylene to be 1.95 mm/ $\mu$ sec. The plastic used in this work was found to have a density of 0.916 g/cc and a room temperature ultrasonic velocity of approximately 1.98 mm/ $\mu$ sec.

The longitudinal wave velocity in Plexiglas is plotted in Fig. 10. All measurements for this material were made using the interpolation timing method. There is close agreement between values obtained at the different frequencies. The same handbook cited previously shows the longitudinal velocity in Lucite to be 2.68 mm/ $\mu$ sec. Lucite and Plexiglas are trade names for the same basic type of plastic, poly(methylmethacrylate). The room temperature

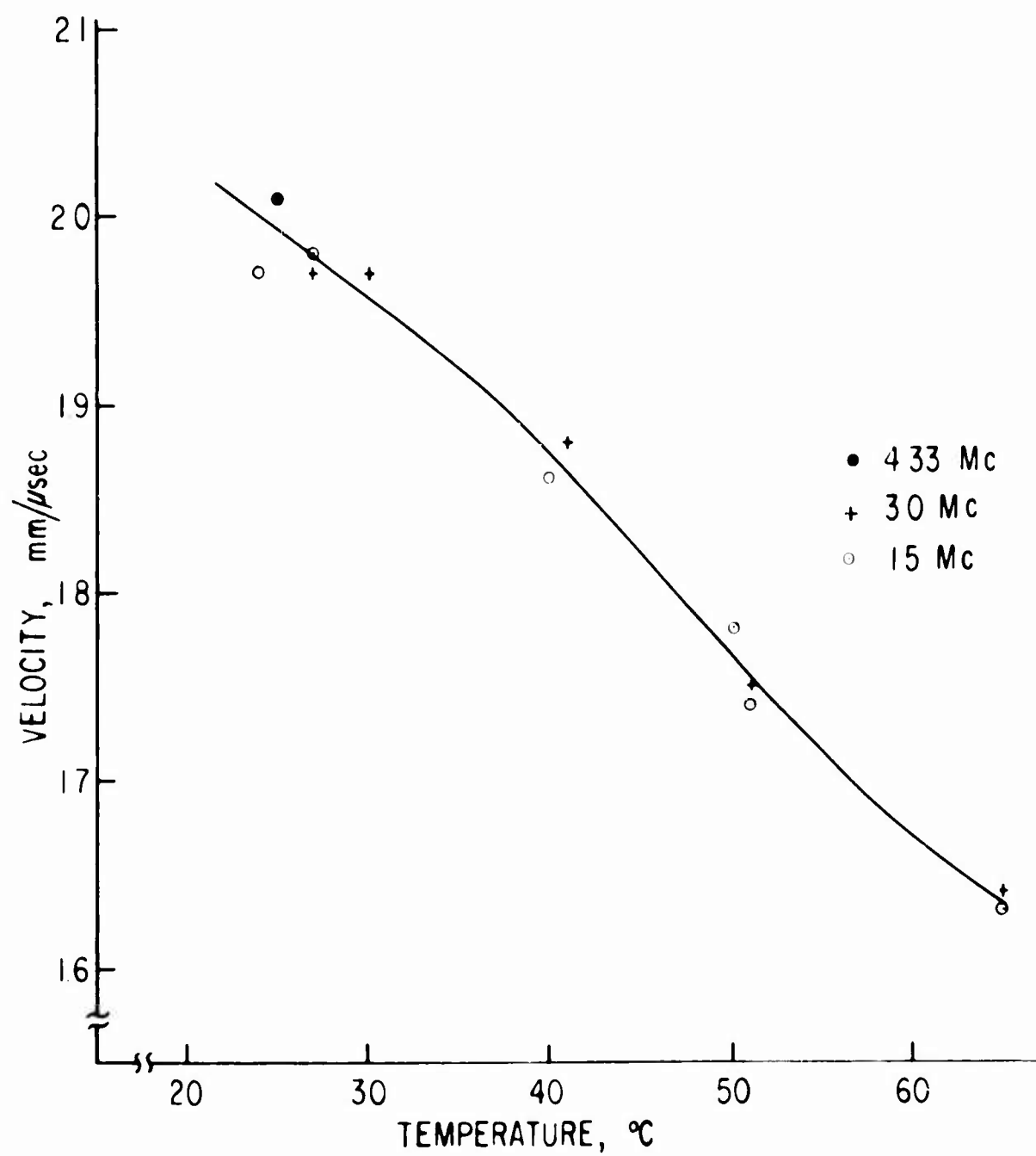


FIGURE 9 LONGITUDINAL VELOCITY IN LOW DENSITY POLYETHYLENE



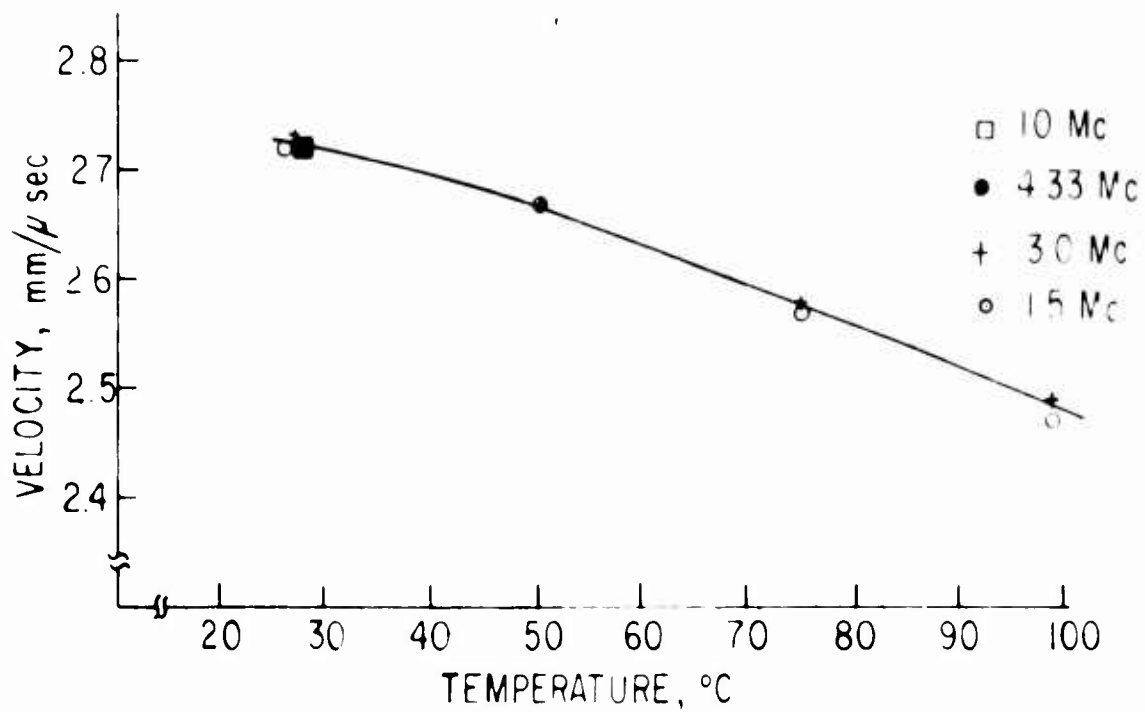


FIGURE 10 LONGITUDINAL WAVE VELOCITY IN PLEXIGLAS

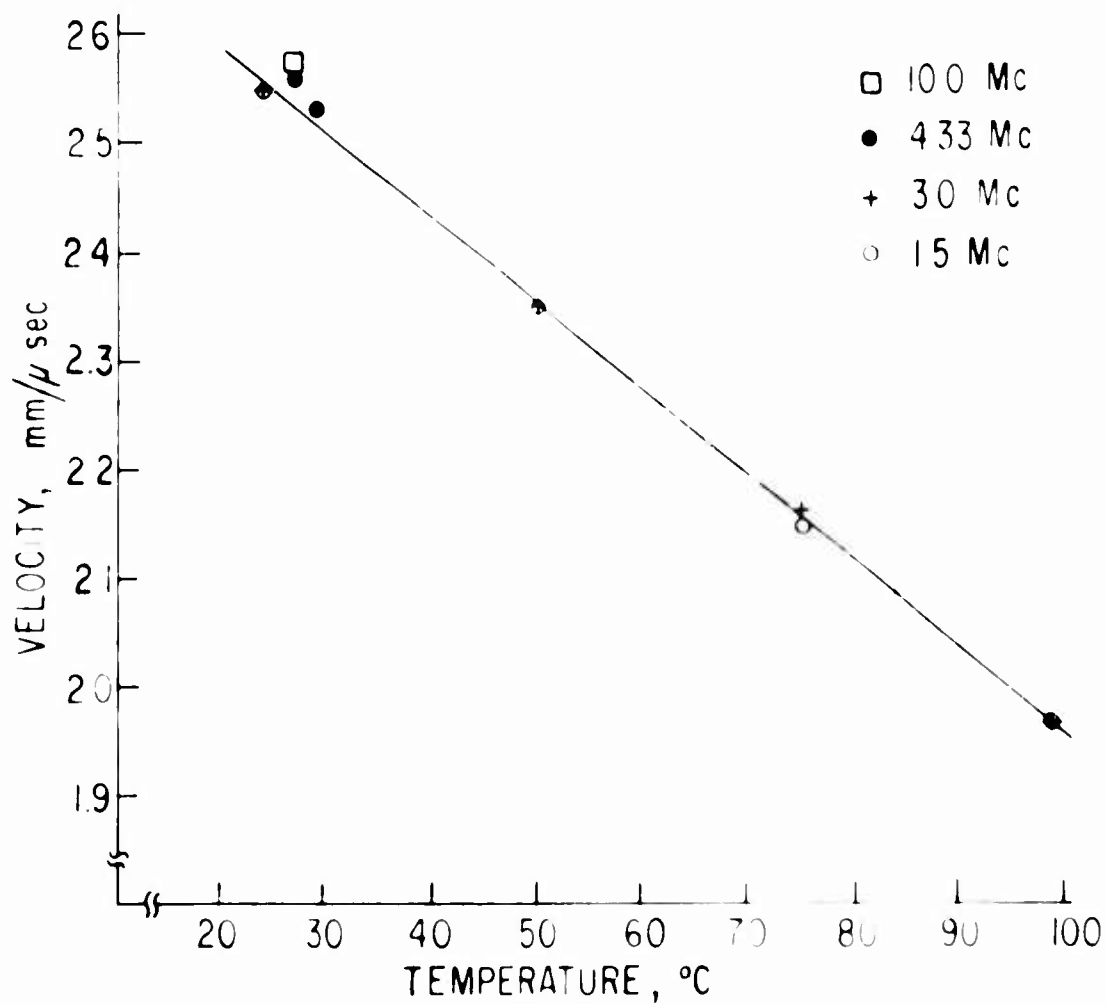


FIGURE 11 LONGITUDINAL VELOCITY IN  
HIGH DENSITY POLYETHYLENE

velocity value experimentally obtained at all four frequencies was 2.72 mm/ $\mu$ sec.

Fig. 11 shows the almost perfectly linear velocity-temperature relationship determined for the high density polyethylene. All measurements were made using the interpolation timing method. A published velocity value for this type of material was not found so no comparison is possible.

The other common plastic investigated was Teflon. For this material the temperature range was extended to below room temperature in order to obtain a more accurate picture of the shape of the velocity curve in the range between 20 and 30 °C. As can be seen in Fig. 12, there is a fairly sharp inflection in the velocity curve in this region. The velocities measured in Teflon appear to be somewhat more frequency sensitive than they were in the other materials. Nevertheless, the difference was not sufficient to justify separate plots, and all measurements at the three frequencies used are plotted on the same graph. A comparison velocity value (with no specification of temperature or frequency) of 1.45 mm/ $\mu$ sec was found in an article by Hastings, LoPilato, and Lynnworth (31). The room temperature value for the Teflon used in this work was found to be somewhat lower, or approximately 1.40 mm/ $\mu$ sec.

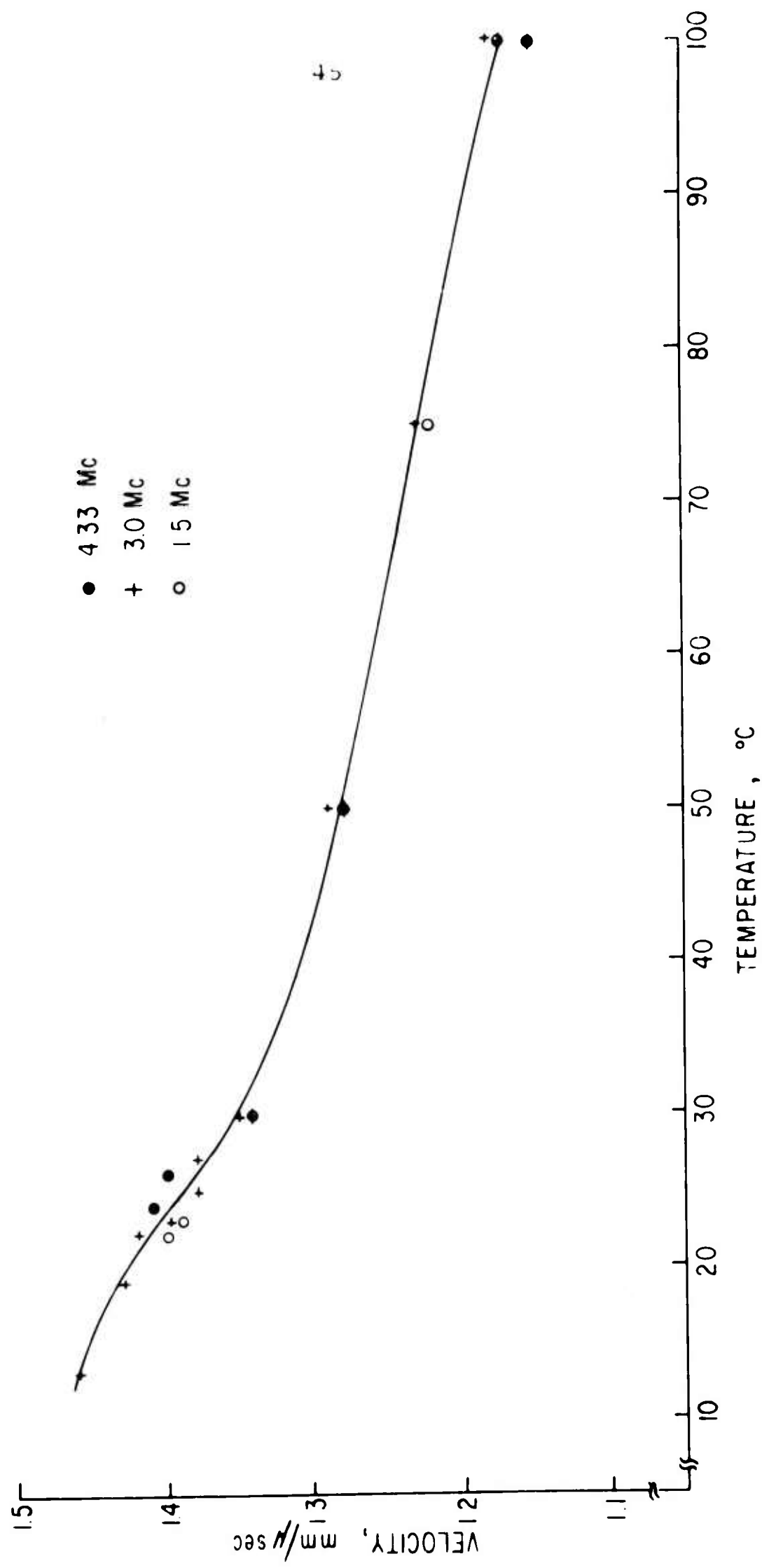


FIGURE 12 LONGITUDINAL WAVE VELOCITY IN TEFLON

The sources of error inherent in this method of measuring ultrasonic velocities fall into four categories. There may be errors in (1) sample thickness measurements, (2) transit time measurements, (3) temperature measurements, or (4) there may be more fundamental errors inherent in the method. These will be discussed in turn.

Sample thicknesses were measured with micrometers. Two new micrometers were available, one of them graduated in the metric system and the other in the English system of measurement. They were calibrated against each other and found to give identical values for the thicknesses of several different samples (with due caution being taken to insure that both measurements of any particular sample were made at the same point on the sample.) Therefore, any error in the micrometers is considered to be negligible.

Two significant problems concerning sample thickness were encountered. The first problem was one of machine shop technique. The early samples made for use in this project were cut on a lathe. The procedure was satisfactory for the thicker samples and typically gave samples varying in thickness by no more than 0.05%. With the thinner and more flexible samples, though, the results were not as good. To cite the worst example, one of the original samples of low density

polyethylene, with a mean thickness of 3.24 mm, was quite irregular and showed a thickness variation of  $\pm 1.7\%$ .

The other problem associated with sample thickness is that some of the plastics studied in this work showed a dimensional instability. Teflon, in particular, exhibited this characteristic. The Teflon samples first received from the machine shop were quite uniform. One sample, for example, had a mean thickness of 9.66 mm with a difference of less than 0.01 mm between the thickest and thinnest measurements recorded. After the samples had been subjected to repeated temperature changes in making velocity determinations, it was noted that the results were becoming increasingly erratic. The samples were remeasured and discovered to be quite irregular. The sample mentioned above was found to have a mean thickness of 9.76 mm, with some spots as thick as 9.91 mm and others as thin as 9.67 mm. The sample had grown thicker and had become uneven. This was probably at least partially due to the relaxation of strains imposed during the machining process.

After this discovery, new samples were made by using a milling process which gave very uniform samples. One of the best was a sample of high density polyethylene. The usual measurement procedure of taking thickness readings at ten different positions on the sample gave eight values of 25.420 mm

and two of 25.421 mm. As a further precaution, frequent checks of sample dimensions were made to reduce the error due to this cause.

The computed velocities have been corrected for thermal expansion by using handbook (32) values for the coefficients of linear expansion.<sup>19</sup> The median values were used in the cases where a range of values was given for the thermal coefficients. This could cause some small amount of error. The worst case would be that of velocity determination for high density polyethylene at 100° C. The corrected velocity may have a relative error of  $\pm 0.5\%$ , depending on the correct value for the coefficient of expansion. For the other materials, with smaller coefficients, the error would be less. The error due to this source would be maximum at the highest temperature used and nonexistent at room temperature.

Errors in time measurement might arise from three sources. The first of these, naturally, is the time-mark generator. As was stated previously, the error in this instrument was less than one part per million. Hence, any error here is considered negligible.

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<sup>19</sup> The values quoted (32) are

nylon	$8.3-10 \times 10^{-5}/\text{deg C}$
polyethylene (all densities)	$15-30 \times 10^{-5}/\text{deg C}$
poly(methylmethacrylate) (Plexiglas)	$9 \times 10^{-5}/\text{deg C}$
Teflon	$5.5 \times 10^{-5}/\text{deg C}$

The interpolation timing method assumes the oscilloscope delay sweep to be sufficiently linear to permit linear interpolation within the  $1\text{ }\mu\text{sec}$  intervals between consecutive time marks. Since all velocity determinations depend on the difference between two times, any error due to this source would tend to be reduced by the subtraction process. This statement depends on the reasonable assumption that all errors due to nonlinearity would be in the same direction. For this reason the error due to oscilloscope nonlinearity is also presumed to be negligible.

The most important source of error in this method of timing is that of operator technique. The oscilloscope delay control potentiometer was read to three decimal places by visual interpolation between the finest graduations on the scale. Admittedly, this calls for good eyesight and careful work, and not too much importance should be attached to the least significant figure. Nonetheless, independent readings of the same time periods by the author and by the technician who assisted him consistently gave results which agreed to within three or four nanoseconds. It is doubted that the error in making any individual time measurement exceeded  $0.01\text{ }\mu\text{sec}$ . Using this figure as the maximum uncertainty in any one reading, the maximum relative uncertainty in the difference between two

readings would be  $0.02/2.4$  or less than 1%. The figure "2.4" is used because the smallest observed difference between two elapsed times was approximately  $2.4 \mu\text{sec}$ . This was the difference between the transit times through two of the nylon samples. The smallest time differences encountered with the other materials ranged from 4 to 6  $\mu\text{sec}$ . For these larger values the proportional uncertainty would be correspondingly less. The superposition timing method gave less repeatability, and it is estimated that the relative uncertainty of the time measurements using superposition was approximately twice as great as with the interpolation method.

The third type of error enumerated above concerns temperature measurements. Temperatures were measured with a thermometer and were recorded to the nearest degree. For the high density polyethylene the linear functional relation between velocity and temperature can be graphically determined from Fig. 11 to be approximately

$$v_{20-100} = 2.58 - 0.0078(T-20)$$

where  $T$  is in degrees Celsius and  $v$  is in  $\text{mm}/\mu\text{sec}$ . Thus an error of one half degree in temperature would cause an apparent error in velocity of  $0.004 \text{ mm}/\mu\text{sec}$ . At the high temperature end of the curve, where the velocity is lower, the relative error would be approximately 0.2%. It would be



less than this in the lower portion of the temperature range. The study of internal sample temperatures described in Appendix C was conducted in an effort to reduce temperature-caused errors.

The sources of error other than those discussed above constitute the fourth category. The errors in this group are not errors in measurement; they are rather errors in concept or in technique to which numerical values cannot readily be assigned. The major premise of the experimental method is that the acoustic units can be assembled accurately enough so that two acoustic assemblies, made up in succession by using two different samples, will differ ultrasonically only because of the difference in sample thicknesses. To test the accuracy with which this ideal was achieved would be difficult and very time-consuming. Because of the large amount of time between measurements that would have been spent waiting for temperature equilibrium, it was not feasible to make a statistically significant number of determinations with any one material. The results obtained indicate that this key assumption was reasonable in view of the limited accuracy that was needed.

Another possible source of error is in picking the reference points on the transmitted and received pulses

between which to measure the elapsed transit time. The received signals did not coincide exactly in shape with the transmitted signals, and some small amount of judgment was necessary in picking the reference points. Usually, however, the oscillations were so clear and well defined that there was no serious doubt about the proper choice.

Some small amount of error may be due to the fact that the received signal was generally slightly longer in duration than was the transmitted pulse. This was probably due to the fact that plastics are dispersive media.

In the determinations made during this study there were not enough measurements made of the same quantity to permit a statistical treatment of the data. However, some maximum error calculations made in Appendix E indicate that the maximum relative uncertainty in velocity is approximately 4%. This is on a pessimistic "worst possible case" basis. Examination of the data points for which multiple velocity determinations have been made reveals less than 3% difference between the maximum and minimum values. It should be recalled that these points include determinations made by different timing methods and at different frequencies. Also included are determinations made with samples which were later discovered

to be quite irregular in thickness. In no case in which the interpolation timing method was used was there more than 1% difference between the values obtained under the same conditions of temperature and frequency.

## CHAPTER 5. SUMMARY

A simple and practical apparatus has been set up in the Air Force Weapons Laboratory to satisfy that laboratory's need for a capacity to measure longitudinal ultrasonic wave velocities. The method used to determine velocity is based on measuring the times required for ultrasonic pulses to travel through samples of different lengths. The method is capable of measuring velocities through samples of a few millimeters thickness with no more than 4% error.

The velocities of longitudinal waves through several plastics have been determined over a range of temperatures that, in general, extended from room temperature up to 100° C.

Five of the materials studied were common plastics for which velocity-temperature curves have been given in this thesis. The other plastics investigated were special-purpose materials used in the nose cones of ballistic re-entry vehicles. Velocity data for these materials was required by another research project being conducted at the Weapons Laboratory.

A technician has been trained in the use of the equipment and has made many velocity determinations.

While the method developed for use in this investigation is not unique, either in concept or in the accuracy achieved, it has provided an effective answer to a real and significant problem. The basic objectives enumerated at the start of the study, namely, to obtain velocity-temperature data not previously available and to provide the Weapons Laboratory with a needed capability, have been achieved.

## APPENDIX A. LONGITUDINAL WAVE VELOCITY IN SOLIDS

The equations of motion in an isotropic elastic medium are given in various texts (5,33) as

$$\rho \frac{\partial^2 u}{\partial t^2} = (\lambda + \mu) \frac{\partial \Delta}{\partial x} + \mu \nabla^2 u \quad (1)$$

$$\rho \frac{\partial^2 v}{\partial t^2} = (\lambda + \mu) \frac{\partial \Delta}{\partial y} + \mu \nabla^2 v \quad (2)$$

$$\rho \frac{\partial^2 w}{\partial t^2} = (\lambda + \mu) \frac{\partial \Delta}{\partial z} + \mu \nabla^2 w \quad (3)$$

where  $\rho$  is the density of the medium;  $\lambda$  and  $\mu$  are the Lamé constants,  $u$ ,  $v$ , and  $w$  are the displacements in the  $x$ ,  $y$ , and  $z$  directions, respectively;  $\Delta$ , the dilatation, is given by

$$\Delta = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} ;$$

and

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} .$$

Kolsky (33) shows that a simple manipulation of the equations above leads to the familiar relation

$$\rho \frac{\partial^2 \Delta}{\partial t^2} = (\lambda + 2\mu) \nabla^2 \Delta \quad (4)$$

for the propagation of a wave (of dilatation, in this case) with the velocity  $\left[ (\lambda + 2\mu) / \rho \right]^{\frac{1}{2}}$ . This is the velocity of propagation of longitudinal waves through an extended elastic

medium. (The transverse wave equations which can also be developed from the same starting point are outside the treatment of this thesis.)

For a plane wave propagating in the x direction, equation (4) reduces to

$$\rho \frac{\partial^2 u}{\partial t^2} = (\lambda + 2\mu) \frac{\partial^2 u}{\partial x^2} . \quad (5)$$

It can easily be verified that a solution of (5) is given by

$$u = u_0 \cos w \left( t - \frac{x}{c} \right) \quad (6)$$

where

$$c = \left( \frac{\lambda + 2\mu}{\rho} \right)^{1/2} . \quad (7)$$

The longitudinal velocity expressed by (7) represents the desired quantity in this experimental investigation. Tu, Brennan, and Sauer (34) show that this is the velocity with which ultrasonic pulses are propagated in a cylindrical rod, provided that the rod's radius is at least 2.5 times as great as the wavelength of the stress disturbance. They also show that, for rods smaller than this in radius, the velocity is a function both of frequency and of the relative diameter of the rod.

To insure that the measured values would represent the propagation velocity of plane waves in an infinite medium

the transmission rods and samples were made with radii of approximately 25 mm. This radius is almost 6 times greater than the longest wavelength used. (The wavelength of 1.5 Mc waves in aluminum is approximately 4.3 mm.)



## APPENDIX B SAMPLE IDENTIFICATION

All of the plastic samples used in acquiring the data given in Chapter 4 were cut as right circular cylinders approximately 2 inches in diameter. As stated in the text, these materials exhibited some dimensional instability. Sample thicknesses are given below which show some of the changes in dimensions which occurred. The general tendency was for the samples to grow thicker and less uniform with the passing of time. Nylon and Plexiglas were the most stable dimensionally; Teflon was least stable.

The materials are listed in the order in which the data was given in Chapter 4. (The identifying numbers were assigned to the materials for convenience in reference during the investigation and have no significance per se.)

Material number 12, Poly-Penco nylon, density 1.15 g/cc:

Measurements taken 24 March 1964:

Sample # 12.1	25.517 ± .008 mm
# 12.2	9.703 ± .005 mm
# 12.3	3.101 ± .018 mm

Measurements taken 11 July 1964 (only mean thicknesses recorded) :

Sample # 12.1	25.52 mm
# 12.2	9.71 mm
# 12.3	3.09 mm

Measurements taken 29 July 1964:

Sample # 12.1	$25.515 \pm .010$ mm
# 12.2	$9.715 \pm .006$ mm

Material number 11, polyethylene, density 0.916 g/cc:

Measurements taken 24 March 1964:

Sample # 11.1	$31.300 \pm .010$ mm
# 11.2	$12.842 \pm .025$ mm
# 11.3	$3.238 \pm .056$ mm

New dimensions after samples were refaced by milling  
(12 July 1964):

Sample # 11.1A	$31.237 \pm .008$ mm
# 11.2A	$12.698 \pm .011$ mm
# 11.3A	$3.044 \pm .005$ mm

Material number 13, Plexiglas, density 1.19 g/cc:

Measurements taken 28 April 1964:

Sample # 13.1	38.07 mm (only mean was recorded)
# 13.2	$18.568 \pm .005$ mm
# 13.3	$3.251 \pm .013$ mm

**Measurements taken 11 July 1964:**

Sample # 13.1	38.097 ± .005 mm
# 13.2	18.603 ± .006 mm
# 13.3	3.251 ± .022 mm

Material number 15, polyethylene, density 0.964 g/cc:

**Measurements taken 15 May 1964:**

Sample # 15.1	25.424 ± .004 mm
# 15.2	12.702 ± .002 mm
# 15.3	3.178 ± .002 mm

**Measurement taken 15 July 1964:**

Sample # 15.3	3.226 ± .003 mm
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New dimensions after samples were refaced by milling  
(15 July 1964):

Sample # 15.1 A	25.420 ± .001 mm
# 15.2 A	12.607 ± .002 mm
# 15.4	2.620 ± .003 mm (new sample)

Material number 10, Teflon, density 2.19 g/cc:

**Measurements taken 24 March 1964:**

Sample # 10.4	19.223 ± .010 mm
# 10.5	9.660 ± .005 mm
# 10.6	2.951 ± .008 mm

**Measurements taken 22 May 1964:**

Sample # 10.4	19.40 ± .18 mm
# 10.5	9.76 ± .15 mm
# 10.6	2.99 ± .02 mm

New dimensions after samples were refaced by milling  
(26 May 1964):

Sample # 10.4A	$18.962 \pm .003$ mm
# 10.5A	$9.530 \pm .006$ mm
# 10.6A	$2.744 \pm .003$ mm

Measurements taken 28 July 1964:

Sample # 10.4A	$18.991 \pm .026$ mm
# 10.5A	$9.549 \pm .018$ mm
# 10.6A	$2.746 \pm .009$ mm

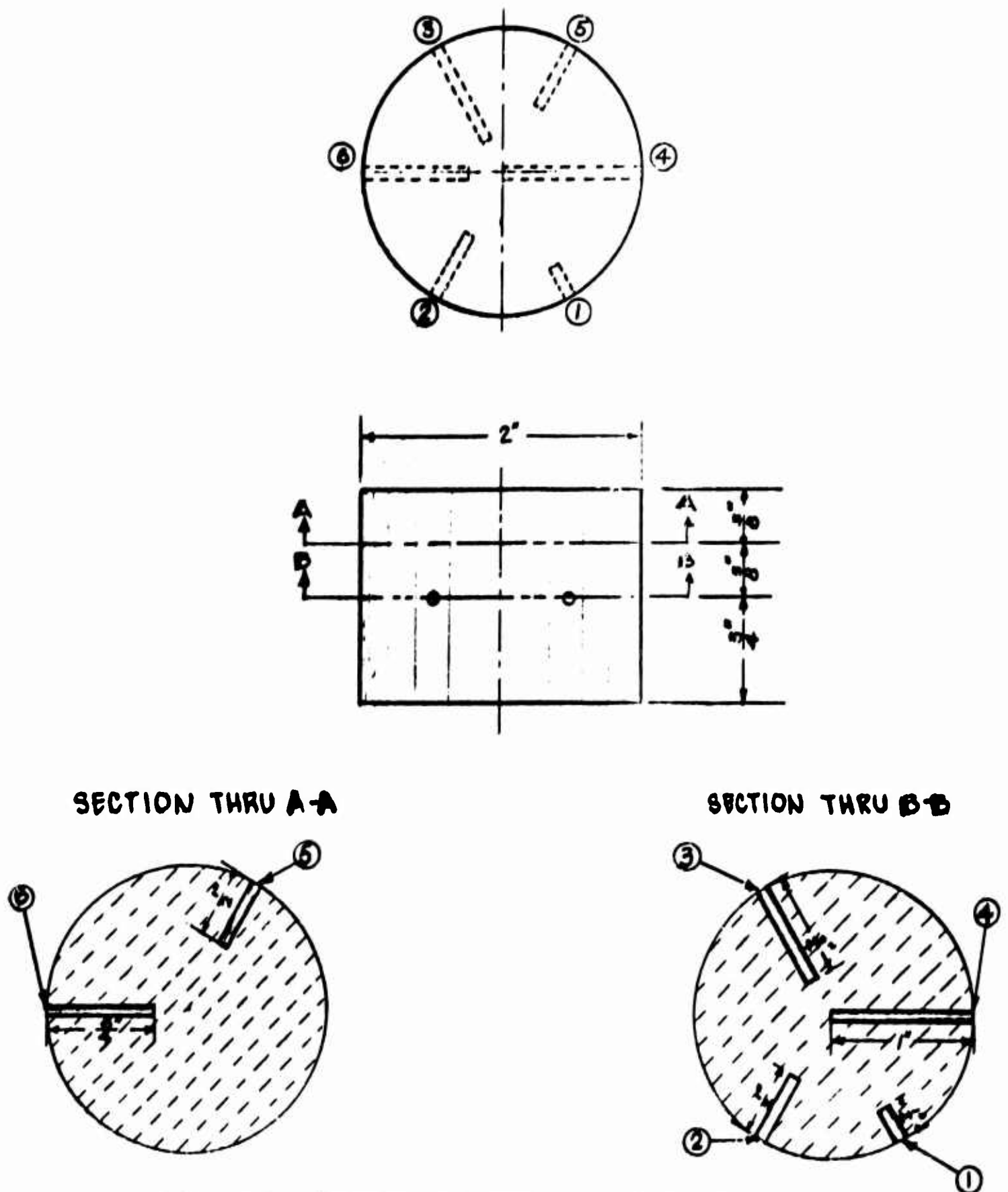
## APPENDIX C. EXPERIMENTAL DATA ON HEATING OF SAMPLES

During this investigation, sample temperature control was provided by a thermostatically controlled oil bath. The sample temperature was determined by reading the temperature of the oil. Therefore, it was necessary to determine the waiting period required from the time of sample immersion until the time of temperature equilibrium. An experimental study of the internal temperatures of several different plastics was conducted to provide a basis for that determination.

Special samples were prepared to allow for the insertion of thermocouples at various places in the sample. Fig. C-1 shows the dimensions of the samples used in finding the curves of temperature versus time which are presented in this appendix.

The thermocouples were made by tightly twisting together the ends of type J iron-constantan thermocouple wire. The six thermocouples used in each sample were cemented in place with an epoxy resin.

The internal temperatures of the samples were determined by measuring the output of the thermocouples with a slide-wire potentiometer. A switching circuit was devised so that two



**Fig. C-1. Sketches of samples used in study of sample heating. Indicated hole numbers correspond to thermocouple numbers in Figs. C-2, C-3.**

samples could be studied at the same time. A 12-position, 2-pole rotary switch was used to connect the twelve thermocouples (six in each sample) to the potentiometer. This allowed the various thermocouples to be read in sequence at one minute intervals. Using this scheme, each thermocouple was read once every twelve minutes. The thermocouple readings, in millivolts, were converted to degrees Celsius by means of a conversion table so that the internal temperatures could be plotted as functions of heating time.

The measurements were made by first heating the oil bath to a selected temperature. Two samples were then immersed in the bath, and thermocouple readings were taken at one minute intervals until it became apparent that no further significant changes would occur.

Two different temperatures, 70° C and 130° C, were used with most of the materials studied. There was no appreciable difference in the times required for equilibrium at the two different temperatures. When the higher bath temperature was used, the sample temperatures simply rose faster and reached equilibrium in about the same length of time as when the lower temperature was used. This is the result to be expected for a linear heat flow problem.

Figs. C-2 and C-3 show the temperature curves obtained by heating samples of Plexiglas and low density polyethylene

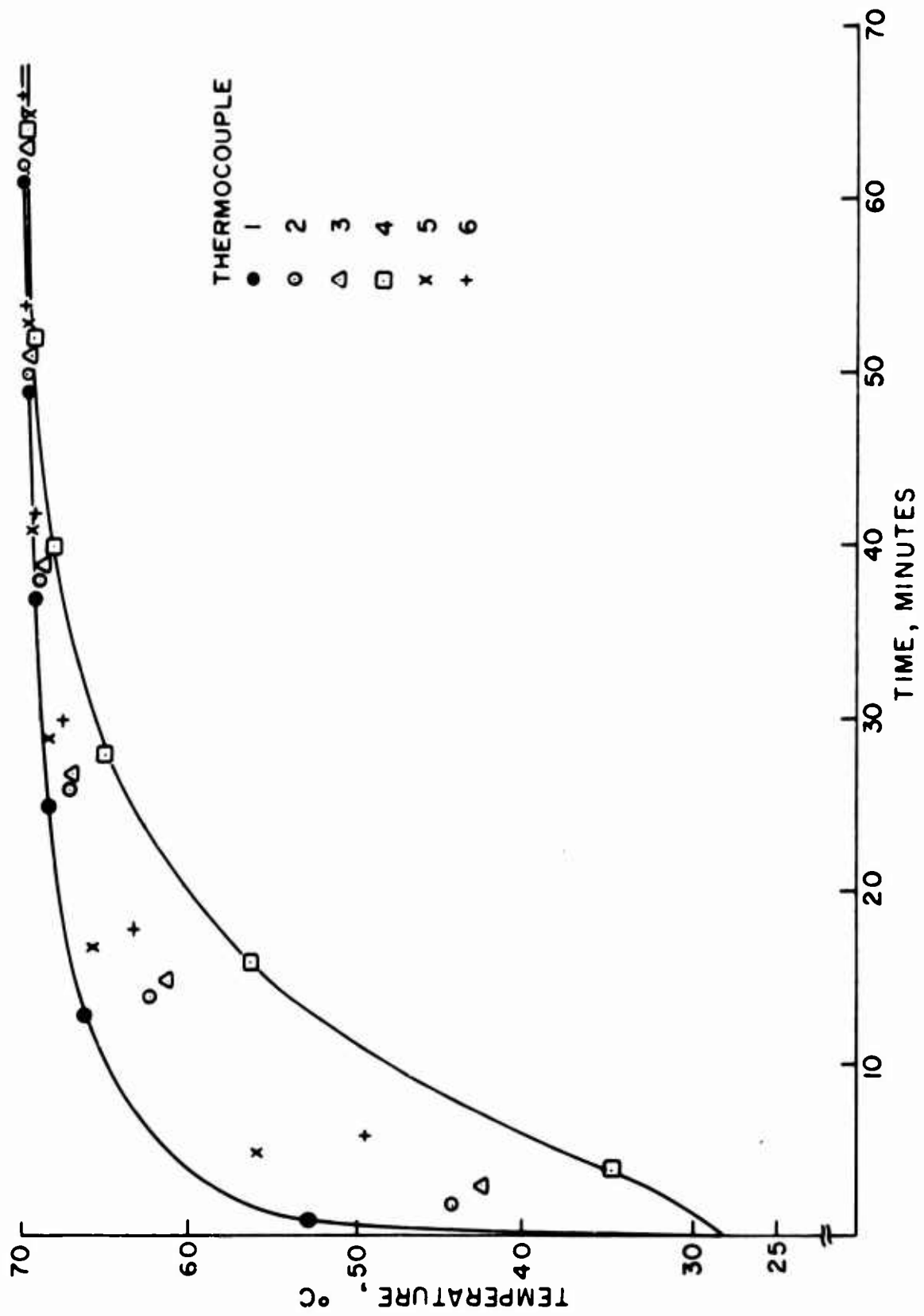


FIGURE C-2 INTERNAL TEMPERATURES OF PLEXIGLAS SAMPLE



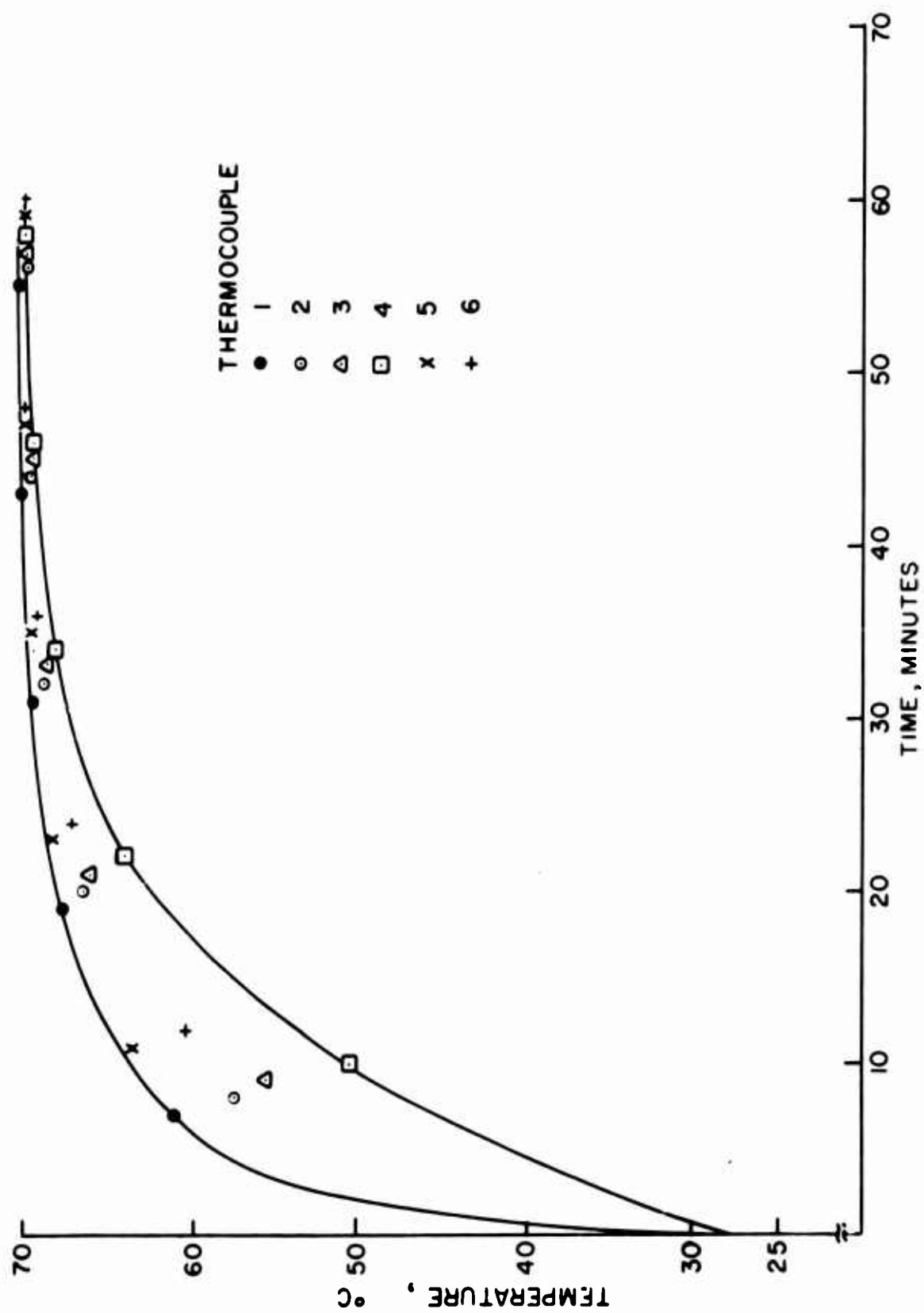
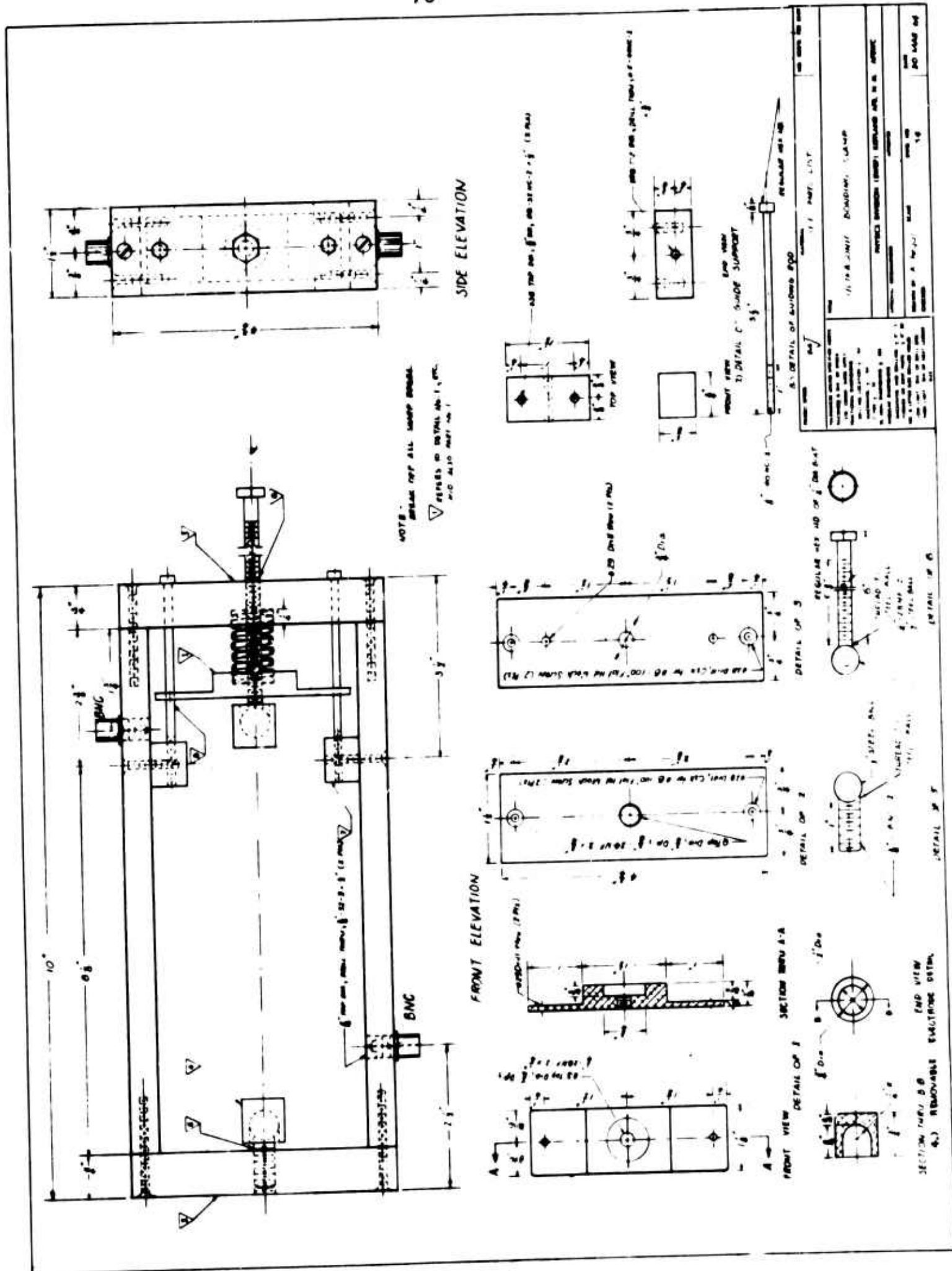


FIGURE C-3 INTERNAL TEMPERATURES OF POLYETHYLENE SAMPLES

in a 70°C bath. (The 130°C bath was too hot for use with these particular materials.) Temperature equilibrium was reached in approximately one hour in both materials.

**APPENDIX D. DRAWINGS OF BONDING CLAMP**



# PARTS LIST FOR DWG. C-54

71

PARTS No.	NAME OF PARTS	REQD NO.	SPECIFICATION	MATL	REMARKS
1		1 EA		STEEL	SEE DWG FOR SHAPE
2		1 EA	$4\frac{3}{4}" \times 1\frac{1}{2}" \times \frac{3}{4}"$	PHENOLIC	" " " "
3		1 EA	$4\frac{3}{4}" \times 1\frac{1}{2}" \times \frac{3}{4}"$	PHENOLIC	" " " "
4	REMOVABLE ELECTRODE	2 EA	OD = $\frac{1}{4}"$ HT = $\frac{3}{4}"$	ALUMINUM	CYLINDER
5	ELECTRODE HOLDER	1 EA	$\frac{3}{8}" - 24 \text{ NF} - 2$ L = 1"	STEEL	$\frac{1}{2}"$ STEEL BALL THREADED 1/16" EGD.
6a	ELECTRODE HOLDER	1 EA	$\frac{1}{4}" - 28 \text{ NF} - 2$ L = 6" LENGTH OF TWO = $5\frac{1}{4}"$	STEEL	TWO $\frac{1}{2}"$ STEEL BALL TO ROD
6b	ELECTRODE HOLDER	1 EA	$\frac{1}{4}" - 28 \text{ NF} - 2$ L = $8\frac{1}{4}"$ LENGTH OF TWO = $8\frac{1}{4}"$	STEEL	TWO $\frac{1}{2}"$ STEEL BALL TO ROD
7	GUIDE SUPPORT	2 EA	$1\frac{1}{2}" \times \frac{3}{4}" \times \frac{3}{4}"$	PHENOLIC	
8	GUIDING ROD	2 EA	$\frac{1}{8}" - 40 \text{ NC} - 2$ L = $3\frac{5}{8}"$	STEEL	
9		2 EA	$3\frac{1}{2}" \times 1\frac{1}{2}" \times \frac{1}{2}"$	ALUMINUM	
10	SCREWS	4 EA	#6 - 100° FLAT HD MACH SCREW		L = $1\frac{3}{4}"$
11	SCREWS	4 EA	#6 - 100° FLAT HD MACH SCREW		L = 1"
12	SPRING	1 EA	OD = $\frac{3}{4}"$ DN =		

Fig. D-2

## APPENDIX E. MAXIMUM ERROR CALCULATIONS

The formulas given in Chapter 4 for the computation of velocity based on measuring elapsed times through three samples are repeated here for convenient reference

$$\begin{aligned}v_{12} &= \frac{x_1 - x_2}{t_1 - t_2} \\v_{13} &= \frac{x_1 - x_3}{t_1 - t_3} \\v_{23} &= \frac{x_2 - x_3}{t_2 - t_3}\end{aligned}\tag{1}$$

In the method used in this work the reported value was the mean of the three values thus obtained, i.e.,

$$v = \frac{v_{12} + v_{13} + v_{23}}{3}\tag{2}$$

Returning to the individual velocity values given by (1), it can be seen that each is obtained as a quotient. In general, that is

$$v = \frac{z}{y}\tag{3}$$

or

$$v = f(z, y)\tag{4}$$

By the chain rule,

$$dv = \left(\frac{\partial v}{\partial z}\right) dz + \left(\frac{\partial v}{\partial y}\right) dy\tag{5}$$

In this case,

$$\frac{\partial v}{\partial z} = \frac{1}{y} ; \quad \frac{\partial v}{\partial y} = -\frac{z}{y^2} . \quad (6)$$

Applying the above to discrete errors,  $\delta v$ ,  $\delta z$ , and  $\delta y$ , one obtains

$$\delta v = \frac{\delta z}{y} + \frac{z \delta y}{y^2} , \quad (7)$$

where the plus sign has been used to obtain the maximum error,  $\delta v$ .

Since  $z = x_i - x_j$ ,

$$\delta z = \delta x_i + \delta x_j . \quad (8)$$

(Again, the plus sign is used to express maximum error.)

Also, since

$$y = t_i - t_j ,$$

$$\delta y = \delta t_i + \delta t_j \quad (9)$$

Substituting in (7)

$$\delta v = \frac{\delta x_i + \delta x_j}{t_i - t_j} + \frac{(x_i - x_j)}{(t_i - t_j)^2} (\delta t_i + \delta t_j) . \quad (10)$$

The relative error is computed by dividing by the velocity, as expressed in (1)

$$\frac{\delta v_{ij}}{v_{ij}} = \frac{\delta x_i + \delta x_j}{x_i - x_j} + \frac{\delta t_i + \delta t_j}{t_i - t_j} . \quad (11)$$

This expression applies in general to any value obtained as the quotient of two differences.

The uncertainty in time measurement can be computed from the formula given in Chapter 3 for the interpolation method of timing, viz.,

$$t = \frac{(p_5 - p_2)}{(p_5 - p_1)} \cdot \frac{(p_5 - p_4)}{(p_6 - p_4)} \cdot t_0 \quad (12)$$

where  $t_0$  is an exact time interval obtained by counting time marks and the  $p_i$ 's are potentiometer readings.

The uncertainty in a sum is the sum of the uncertainties of the terms in the sum. Thus, if

$$t = z + y,$$

then

$$\delta t = \delta z + \delta y.$$

Using this, the maximum uncertainty in (12) is

$$\delta t = \delta \left[ \frac{p_5 - p_2}{p_5 - p_1} \right] + \delta \left[ \frac{p_5 - p_4}{p_6 - p_4} \right] \quad (13)$$

Applying equation (10) to each of the terms on the right hand side gives the expression for the uncertainty in time measurement:

$$\begin{aligned} \delta t = & \frac{\delta p_5 + \delta p_2}{p_5 - p_1} + \frac{(p_5 - p_2)(\delta p_5 + \delta p_1)}{(p_5 - p_1)^2} + \frac{\delta p_5 + \delta p_4}{p_6 - p_4} \\ & + \frac{(p_5 - p_4)(\delta p_6 + \delta p_4)}{(p_6 - p_4)^2} \end{aligned} \quad (14)$$



For the sake of obtaining a numerical value for  $\delta t$ , it is now assumed that  $(p_3 - p_1) = (p_6 - p_4) = 0.99$ , a typical value for a  $1 \mu\text{sec}/\text{cm}$  oscilloscope time base. Further, it is assumed that the uncertainty in the potentiometer readings is one half of the finest scale graduation, i.e.,

$$\delta p_1 = \delta p_2 = \delta p_3 \dots 0.005$$

Reference to Fig. 7 in Chapter 3 shows that  $p_1 \leq p_2 \leq p_3$  and  $p_4 \leq p_5 \leq p_6$ . Hence, there exist the inequalities

$$0 \leq (p_3 - p_2) \leq (p_3 - p_1)$$

and

$$0 \leq (p_5 - p_4) \leq (p_6 - p_4) \quad (15)$$

Substitution of these inequalities and the assumed values into (14) gives the range of the uncertainty in the time measurement

$$\frac{0.02}{0.99} \leq \delta t \leq \frac{0.04}{0.99}$$

$$0.02 \leq \delta t \leq 0.04 \quad (\mu\text{sec}) \quad (16)$$

Similar calculations for an oscilloscope time base of  $2 \mu\text{sec}/\text{cm}$ , where  $(p_3 - p_1) = (p_6 - p_4) \approx 0.5$  gives the range

$$0.04 \leq \delta t \leq 0.08 \quad (\mu\text{sec}) \quad (17)$$

For a time base of  $5 \mu\text{sec}/\text{cm}$ ,  $(p_3 - p_1) = (p_6 - p_4) \approx 0.2$ , and the range of maximum error becomes

$$0.10 \leq \delta t \leq 0.20 \quad (\mu\text{sec}) \quad (18)$$

These are maximum errors and could be achieved only by a combination of very careless work and bad luck. Nevertheless, the maximum value in each range will be used in the ensuing calculation to give the worst possible case. The sample dimensions used below are the actual dimensions of the first low density polyethylene samples used. The error in these samples was greater than in any other set. For ease of calculation, the correct velocity of longitudinal waves in polyethylene is assumed to be 2.00 mm/ $\mu$ sec. It is also assumed that the sum of all delays plus the transit time through the transmission block is 3  $\mu$ sec.

The sample thicknesses are  $x_1 = 31.30 \pm .01$  mm.,  $x_2 = 12.84 \pm .03$  mm., and  $x_3 = 3.24 \pm .06$  mm. The "correct" transit times (including the constant 3  $\mu$ sec delay) are given by the expressions

$$\begin{aligned} t_1 &= \frac{31.30 \text{ mm}}{2.00 \text{ mm}/\mu\text{sec}} + 3 \mu\text{sec} = 18.65 \mu\text{sec} \\ t_2 &= \frac{12.84}{2.00} + 3 = 9.42 \mu\text{sec} \\ t_3 &= \frac{3.24}{2.00} + 3 = 4.62 \mu\text{sec} \end{aligned} \quad (19)$$

The interval  $t_1$  would have to be measured using a time base of 5  $\mu$ sec/cm. The maximum error is given by (18).

Therefore,

$$\delta t_1 = 0.2 \mu\text{sec} .$$

The time  $t_2$  could be measured using a time base of 2  $\mu\text{sec}/\text{cm}$ . Therefore, (17) applies and

$$\delta t_2 = 0.08 \mu\text{sec}.$$

The short time interval,  $t_3$ , could be measured using a 1  $\mu\text{sec}/\text{cm}$  time base so the maximum uncertainty is

$$\delta t_3 = 0.04 \mu\text{sec}.$$

Substituting the values shown above for the uncertainties in time and distance measurements into equation (11) gives the maximum relative uncertainties of the three velocities.

$$\frac{\delta v_{12}}{v_{12}} = \frac{0.01 + 0.03}{31.30 - 12.84} + \frac{0.2 + 0.08}{18.65 - 6.42} = 0.032$$

$$\frac{\delta v_{13}}{v_{13}} = \frac{0.01 + 0.06}{31.30 - 3.24} + \frac{0.2 + 0.04}{18.65 - 4.62} = 0.019$$

$$\frac{\delta v_{23}}{v_{23}} = \frac{0.03 + 0.06}{12.84 - 3.24} + \frac{0.08 + 0.04}{6.42 - 4.62} = 0.034.$$

Thus the maximum relative uncertainties for these velocities could be between 2 and 3%. (It is conceivable that a myopic machinist with dull tools could make poorer samples than those used in this calculation. The time errors, however, are as great as could be achieved.)

The reported velocity was computed as the arithmetic mean of the three individual velocities determined above.

Since  $v_{12}$ ,  $v_{13}$ , and  $v_{23}$  are not independent, it is impossible for all of them to simultaneously represent the worst possible

case. Therefore, the uncertainty of the mean is not one third of the sum of the individual uncertainties. By a series of computations using the extreme (i.e., the thickest and the thinnest) values for the thicknesses of the three samples it can be seen that, if there is no error in time measurements, the minimum mean velocity is computed by using the following values for the sample thicknesses:

$$\begin{aligned}x_1 - \delta x_1 &= 31.29 \text{ mm} \\x_2 - \delta x_2 &= 12.81 \text{ mm} \\x_3 + \delta x_3 &= 5.50 \text{ mm}\end{aligned}\tag{21}$$

Under the same assumption of no time error, the maximum mean velocity is computed by using, as sample thicknesses, the values

$$\begin{aligned}x_1 + \delta x_1 &= 31.51 \text{ mm} \\x_2 + \delta x_2 &= 12.87 \text{ mm} \\x_3 - \delta x_3 &= 5.18 \text{ mm}\end{aligned}\tag{22}$$

Another series of computations using the extreme time values possible gives the set of time values which combine with the thicknesses listed in (21) to give the minimum mean velocity:

$$\begin{aligned}v_{12} &= \frac{(x_1 - \delta x_1) - (x_2 - \delta x_2)}{(t_1 + \delta t_1) - (t_2 + \delta t_2)} = \frac{18.48}{9.35} = 1.976 \\v_{13} &= \frac{(x_1 - \delta x_1) - (x_3 + \delta x_3)}{(t_1 + \delta t_1) - (t_3 - \delta t_3)} = \frac{27.99}{14.27} = 1.961\end{aligned}\tag{23}$$

$$v_{23} = \frac{(x_2 - \delta x_2) - (x_3 + \delta x_3)}{(t_2 + \delta t_2) - (t_3 - \delta t_3)} = \frac{9.51}{4.92} = 1.933 \quad .$$

The mean velocity is

$$v_{\min} = \frac{v_{12} + v_{13} + v_{23}}{3} = 1.957 \approx 1.96 \text{ mm}/\mu\text{sec} \quad . \quad (24)$$

The maximum mean velocity is computed using the thicknesses shown in (22) and the times shown in the following calculations:

$$v_{12} = \frac{(x_1 + \delta x_1) - (x_2 + \delta x_2)}{(t_1 - \delta t_1) - (t_2 - \delta t_2)} = \frac{18.44}{9.11} = 2.024$$

$$v_{13} = \frac{(x_1 + \delta x_1) - (x_3 - \delta x_3)}{(t_1 - \delta t_1) - (t_3 + \delta t_3)} = \frac{28.13}{13.79} = 2.040 \quad (25)$$

$$v_{23} = \frac{(x_2 + \delta x_2) - (x_3 - \delta x_3)}{(t_2 - \delta t_2) - (t_3 + \delta t_3)} = \frac{9.69}{4.68} = 2.071 \quad .$$

The maximum mean velocity is

$$v_{\max} = \frac{v_{12} + v_{13} + v_{23}}{3} = 2.045 \approx 2.05 \text{ mm}/\mu\text{sec} \quad . \quad (26)$$

From (24) and (26) it is seen that the maximum uncertainty in the reported velocity is

$$\frac{\delta v}{v} = \frac{.04}{2.00} = 0.02 \quad . \quad (27)$$

By use of the interlocked velocity calculations based on three samples, the maximum uncertainty in the reported velocity is 2%, whereas the maximum uncertainty in any one velocity computed from only two samples may be as high as 3.4%. (See equation (20).)

The effect of a temperature error of one half the finest graduation on the thermometer ( $\delta T = 0.5^\circ \text{C}$ ) was discussed in Chapter 4. The maximum relative uncertainty due to this cause was found to be about 0.2%.

The other sources of error mentioned in Chapter 4 do not involve measurements and cannot be assigned numerical values. Therefore, it is assumed that the relative error due to these sources is equal to the maximum relative error caused by poor measurements. Based on this assumption, the total maximum relative error would be 4.4%. This is less than the allowable error of 5%.

## APPENDIX F. VELOCITY DATA FOR NOSE CONE MATERIALS

As was stated in the introduction, permission to include this information was given after the final writing of the body of the thesis was completed. In certain of these materials, the measurement of ultrasonic velocities is very difficult, and the results obtained should be viewed with suspicion. This is particularly true in the case of the laminated materials. In the graphs which follow, it will be noted that fairly complete and self-consistent sets of measurements have been obtained for some of the materials. In other cases, the results have been poor, and further study is needed.

The velocity values given in this appendix have not been corrected for thermal expansion since the coefficients of expansion are not known. It is estimated that this error causes the reported velocities to be from 1 to 2% low at the higher temperatures. (A discussion of the thermal expansion of the five common plastics used in this work is included in Chapter 4.)

The two materials represented in Fig. F-1 are chopped nylon phenolic (CNP), with a density of 1.68 g/cc, and Castable 124 (C124), with a density of 1.22 g/cc. In the CNP, the axis of propagation was approximately perpendicular to the reinforcing material.

Fig. F-2 shows the velocity through two different orientations of tape wound nylon phenolic (TWNP). In the case of the "oblique" samples, the axis of propagation made an angle of approximately  $54^\circ$  with the layers of the cloth laminate. The samples used to obtain the "perpendicular" data were cut so that the layers of cloth were parallel to the end faces, making the axis of propagation perpendicular to the layers. (The density of the TWNP used here was 1.21 g/cc.)

The next graph, Fig. F-3, shows the velocities measured in two similar materials, Avcoat I (yellow, density 1.10 g/cc) and Avcoat 19 (green, density 1.07 g/cc). The temperature range reported here was reduced to extend between room temperature and  $75^\circ\text{C}$ . Measurements were attempted at higher temperatures, but the results were certainly in error because the materials became very soft and visibly distorted under even moderate pressure from the spring of the bonding clamp.



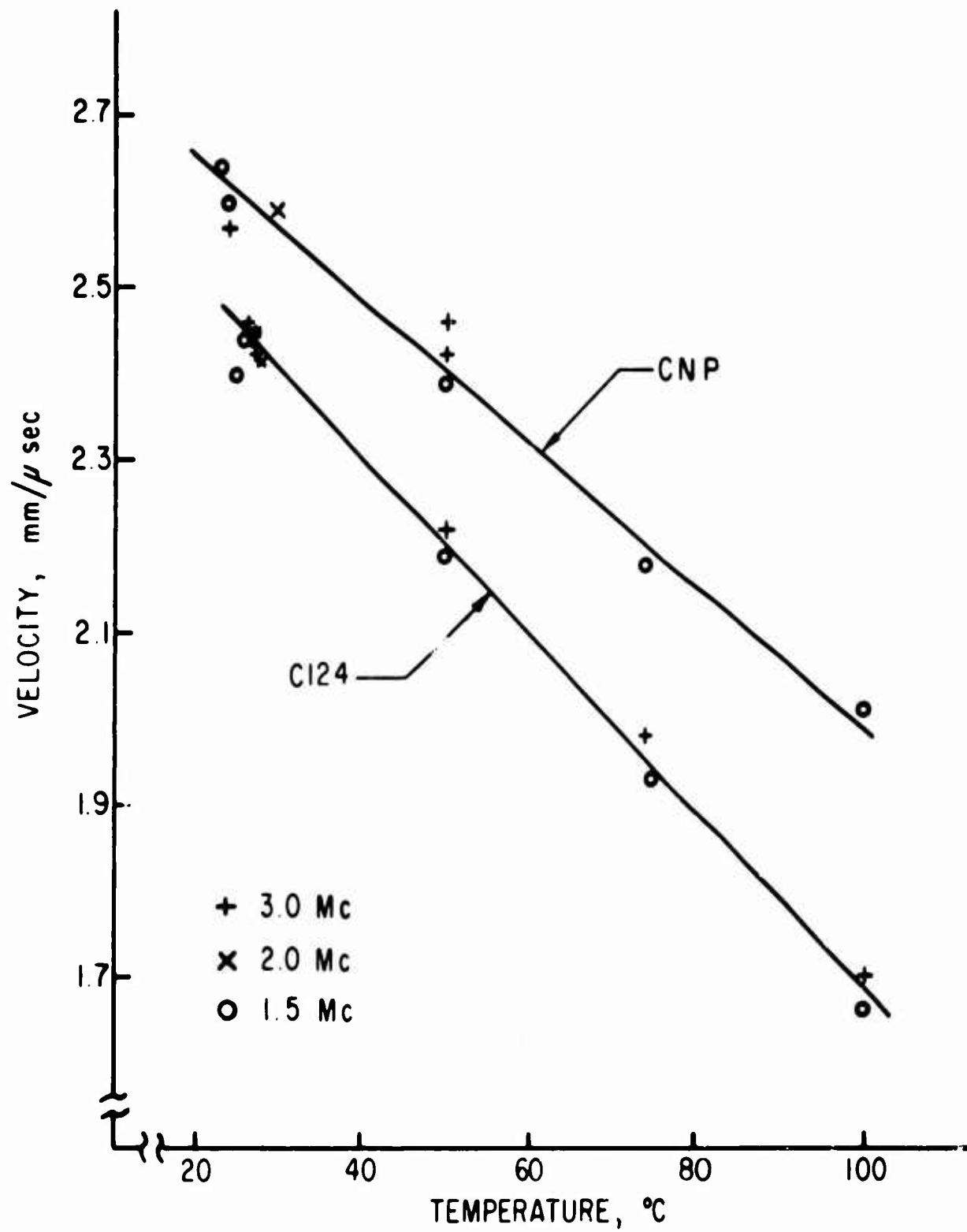


FIGURE F-1 LONGITUDINAL WAVE VELOCITIES IN  
CNP AND CI24

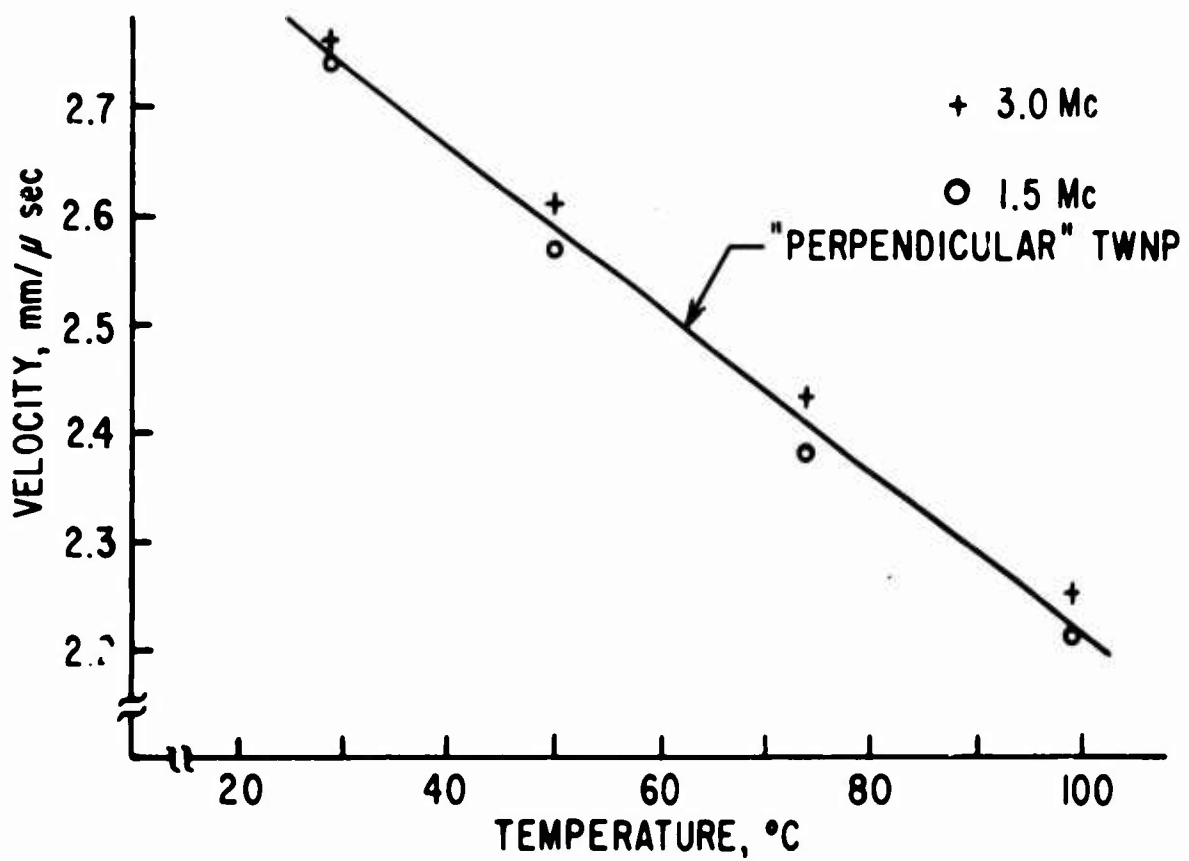
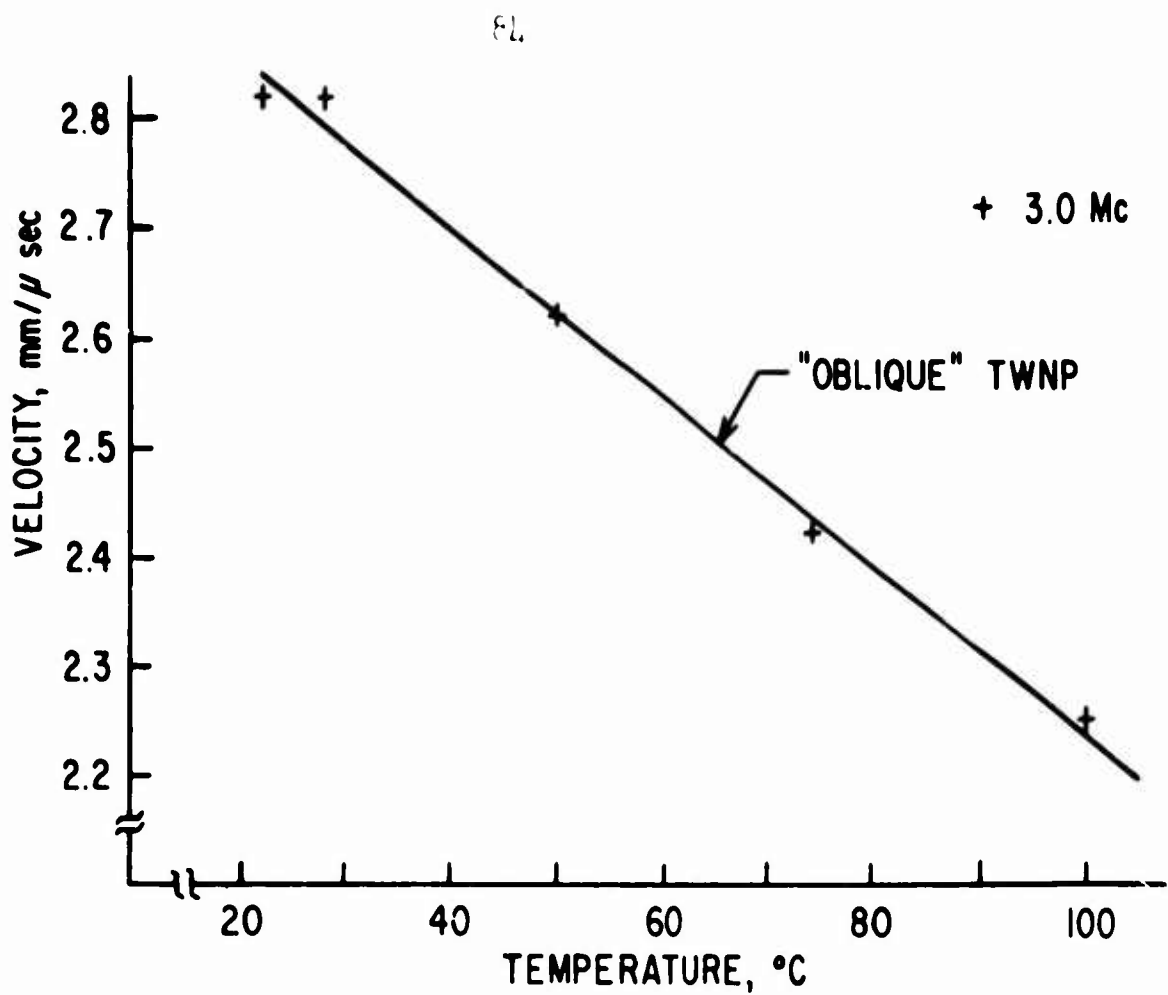


FIGURE F-2- VELOCITY IN TWNP

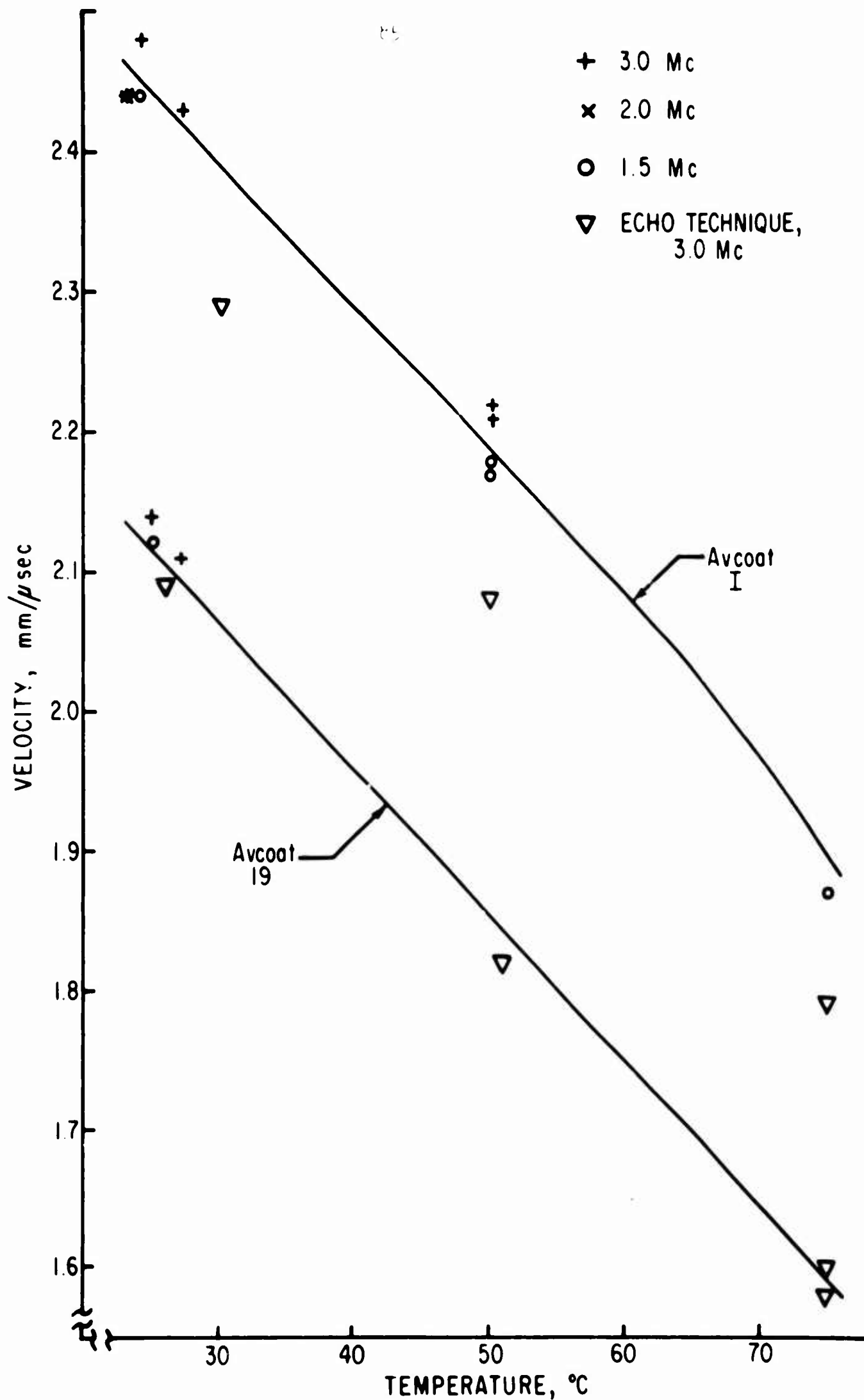


FIGURE F-3 LONGITUDINAL WAVE VELOCITIES IN AVCOAT I AND AVCOAT 19

Attenuation through these samples increased greatly at elevated temperatures, and the measurements could only be made using thinner samples and/or lower frequencies. As indicated in Fig. F-3, velocity measurements in Avcoat 19 were made by two different techniques. Measurements were first made at room temperature by measuring transit times through two different thicknesses of material. This method did not work well at 50° C because of excessive attenuation through the thicker sample (19 mm). Therefore, the echo technique described in Chapter 3 was used by placing the thinner sample (3.5 mm) between two aluminum transmission rods. This method gave good agreement with the values previously determined at room temperature and was, therefore, used for the measurements at 50° C and 75° C. A linear relationship between temperature and velocity was obtained over the temperature range covered.

An attempt was made to use the same echo technique with a thin sample of Avcoat I. This method gave results which were between 4 and 5% lower than those obtained by measuring transit times through two or more different samples. The reason for this difference is not known. It is noted, however, that the slopes of the curves obtained by the two different methods are approximately the same. This makes

it fairly safe to assume that the proper slope for the velocity-temperature curve has been determined. Greater credence is given to the several consistent values obtained by using more than one sample. For this reason, the upper curve in Fig. F-3 was drawn through the points obtained by this method.

Two different configurations of Avco phenolic fiber glass (Avco FG)<sup>20</sup> samples were used. When the axis of propagation of the ultrasonic waves was perpendicular to the reinforcing layers of glass it was found that, for frequencies higher than about 1 Mc, the material apparently acted as a low-pass filter. When frequencies higher than this were transmitted into a sample, the received signal was observed to have a lower frequency than that of the transmitted signal. At a frequency of 1 Mc or below, however, the transmitted and received signals were identical in frequency. (Filtration of acoustic signals by layered media is discussed by Lindsay (35), among others.) In addition, the attenuation of ultrasonic waves passing through this material perpendicular to the layers increased greatly with increasing temperature. For these reasons, the only measurements made of the "perpendicular" velocity were at

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<sup>20</sup>density of 1.70 g/cc.

room temperature and at a frequency of 1 Mc. The longitudinal velocity under these conditions was found to be 2.3 mm/ $\mu$ sec.

The results obtained by passing longitudinal waves through the material in a direction parallel to the layers are shown in Fig. F-4. The figure shows that the velocity of waves parallel to the layers is much higher than that of waves traveling perpendicular to the layers. The dependence of ultrasonic velocity on the direction of transmission through materials of this type has been reported by Hand (36).

A similar dependence of velocity on the direction of propagation was noted in the case of General Electric phenolic fiber glass (GEFG).<sup>21</sup> Fig. F-5 shows the velocity measurements made at temperatures between 25° C and 75° C for waves traveling perpendicular to the laminations.

The velocity of waves moving parallel with the laminations of GEFG was measured at 26° C using frequencies of 1.5 and 3.0 Mc. The values obtained were 4.3 mm/ $\mu$ sec for 1.5 Mc waves and 4.2 mm/ $\mu$ sec for 3.0 Mc waves. These values agree very closely with similar measurements in Avco FG. Further velocity determinations in GEFG were not made because of time limitations. It is, however, expected that the velocity of waves traveling parallel with the layers would be similar to those observed

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<sup>21</sup> density of 1.85 g/cc.

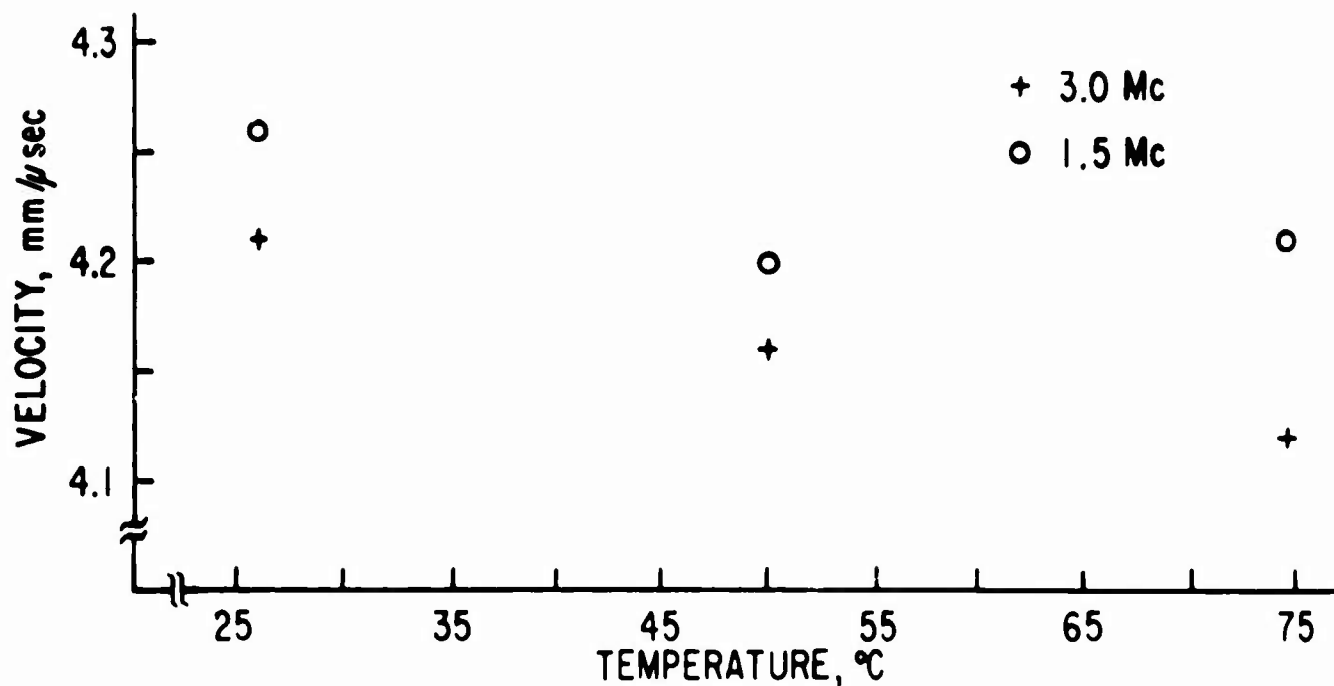


FIGURE F-4 - LONGITUDINAL WAVE VELOCITY IN AVCO FG  
(PARALLEL WITH LAYERS)

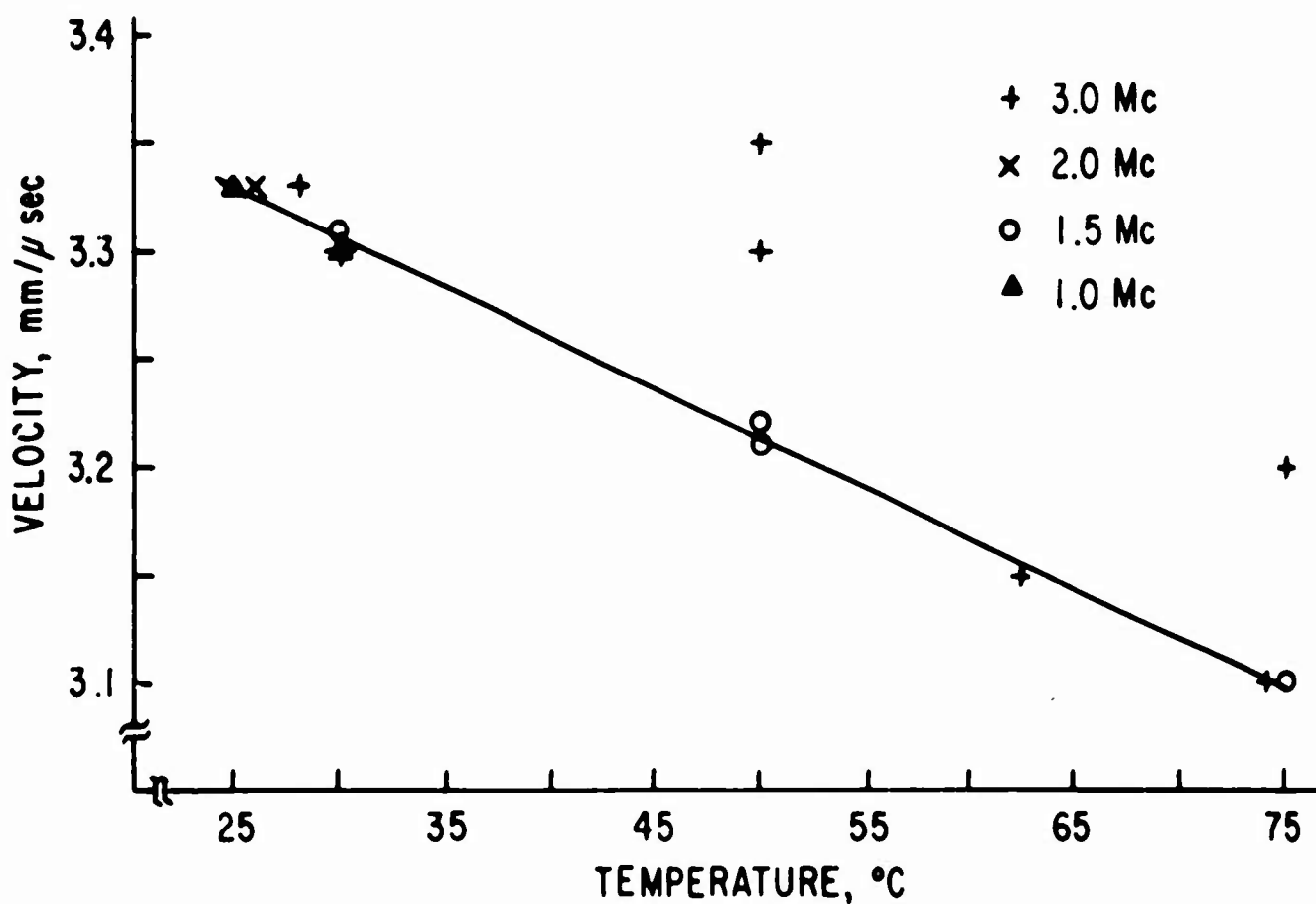


FIGURE F-5 - LONGITUDINAL WAVE VELOCITY IN GEFG  
(PERPENDICULAR TO LAYERS)

in Avco FG since the velocity of propagation in this direction appears to be primarily determined by the velocity of acoustic waves in the laminating material itself.

Numerous efforts to take meaningful velocity measurements in oblique tape wound refrasil (OTWR)<sup>22</sup> were unsuccessful in that very erratic results were obtained. As in the case of the other anisotropic and inhomogeneous materials, different samples were cut so as to study the effect of the direction of propagation (with respect to the laminations) on the velocity of propagation.

The best that can be said is that, between 25°C and 75°C, the velocity of waves traveling perpendicular<sup>23</sup> to the layers was found to lie in the range between approximately 2.5 and 2.9 mm/μsec. Waves traveling parallel with the layers appear to have a velocity of approximately 2.3 mm/μsec.

OTWR also appeared to act as an acoustic low-pass filter, and only frequencies of 1.0 or 1.5 Mc were used for most of the measurements made with this material.

One thin piece of RAD-60 was available for use as a sample. A measurement of velocity through this sample was

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<sup>22</sup> density of 1.54 g/cc.

<sup>23</sup> Since the layers in OTWR are irregular and not planar, no single direction can properly be described as either perpendicular to, or parallel with, the layers.



made at room temperature using the echo technique and a frequency of 3.0 Mc. The value of 2.9 mm/ $\mu$ sec was obtained. This was not checked, and is subject to question.

## LIST OF REFERENCES

- (1) American Institute of Physics Handbook, 2nd ed., McGraw-Hill Book Co., New York, 1963.
- (2) Strutt, John William, 3rd Baron Rayleigh, The Theory of Sound, Vols. I, II, 1st American ed., Dover Publications, New York, 1945. (Vol. I was originally published in London, 1877. Vol. II, 1878. Second edition, London, Vol. I, 1894. Vol. II, 1896.
- (3) Carlin, Benson, Ultrasonics, 2nd ed., McGraw-Hill Book Co., New York, 1960.
- (4) Crawford, Alan E., Ultrasonic Engineering, Butterworths Scientific Publications, London, 1955.
- (5) Mason, Warren P., Physical Acoustics and the Properties of Solids, D. Van Nostrand Co., Inc., Princeton, New Jersey, 1958.
- (6) Mason, Warren P., Piezoelectric Crystals and Their Applications to Ultrasonics, D. Van Nostrand Co., Inc., Princeton, New Jersey, 1950.
- (7) Hueter, Theodor F., and Richard H. Bolt, Sonics, John Wiley and Sons, Inc., New York, 1955.
- (8) Hearmon, R. F. S., "The Elastic Constants of Anisotropic Materials," *Revs. Modern Phys.*, vol. 18, pp. 409-440, July, 1946.
- (9) Huntington, H. B., "The Elastic Constants of Crystals," Solid State Physics, ed. Frederick Seitz and David Turnbull, vol. 7, Academic Press, New York, 1958, pp. 213-351.
- (10) McSkimin, H. J., "Notes and References for the Measurement of Elastic Moduli by Means of Ultrasonic Waves," *J. Acoust. Soc. Am.*, vol. 33, pp. 606-615, May, 1961.

- (11) Quimby, S. J., "On the Experimental Determination of Viscosity of Vibrating Solids," *Phys. Rev.*, vol. 25, pp. 558-573, April, 1925.
- (12) Debye, P., and F. W. Sears, "On the Scattering of Light by Supersonic Waves," *Proc. Natl. Acad. Sci. U. S.*, vol. 18, pp. 409-414, June 15, 1932.
- (13) Willard, G. W., "Improved Methods for Measuring Ultrasonic Velocity," *J. Acoust. Soc. Am.*, vol. 23, pp. 83-93, January, 1951.
- (14) Nolle, A. W., and S. C. Mowry, "Measurement of Ultrasonic Bulk-Wave Propagation in High Polymers," *J. Acoust. Soc. Am.*, vol. 20, pp. 432-439, July, 1948.
- (15) Ivey, D. G., Mrowca, B. A., and E. Guth, "Propagation of Ultrasonic Bulk Waves in High Polymers," *J. Appl. Phys.*, vol. 20, pp. 486-492, June, 1949.
- (16) Huntington, H. B., "Ultrasonic Measurements on Single Crystals," *Phys. Rev.*, vol. 72, pp. 321-331, August 15, 1947.
- (17) Kittel, Charles, Introduction to Solid State Physics, 2nd. ed., John Wiley and Sons, Inc., New York, 1956.
- (18) Lazarus, David, "The Variation of the Adiabatic Elastic Constants of KCl, NaCl, CuZn, Cu, and Al with Pressure to 10,000 Bars," *Phys. Rev.*, vol. 76, pp. 545-553, August 15, 1949.
- (19) Eros, S., and J. R. Reitz, "Elastic Constants by the Ultrasonic Pulse Echo Method," *J. Appl. Phys.*, vol. 29, pp. 683-686, April, 1958.
- (20) Nolle, A. W., and P. W. Sieck, "Longitudinal and Transverse Ultrasonic Waves in a Synthetic Rubber," *J. Appl. Phys.*, vol. 23, pp. 888-894, August, 1952.
- (21) Frederick, J. R., "Ultrasonic Measurement of the Elastic Properties of Polycrystalline Materials at High and Low Temperatures," *J. Acoust. Soc. Am.*, vol. 20, p. 586, July, 1948.

- (22) Bell, J. F. W., "The Velocity of Sound in Metals at High Temperatures," *Phil. Mag.*, ser. 8, vol. 2, pp. 1113-1120, September, 1957.
- (23) Krause, J. T., "Differential Path Method for Measuring Ultrasonic Velocities in Glasses at High Temperatures," *J. Acoust. Soc. Am.*, vol. 35, pp. 1-4, January, 1963.
- (24) McSkimin, H. J., "Use of High Frequency Ultrasound for Determining the Elastic Moduli of Small Specimens," *I.R.E. Trans. on Ultrasonics Engr.*, vol. PGUE-5, pp. 25-43, August, 1957.
- (25) Holbrook, Richard D., "A Pulse Method for Measuring Small Changes in Ultrasonic Velocity in Solids with Temperature," *J. Acoust. Soc. Am.*, vol. 20, p. 590, July, 1948.
- (26) McSkimin, H. J., "Ultrasonic Measurement Techniques Applicable to Small Solid Specimens," *J. Acoust. Soc. Am.*, vol. 22, pp. 413-418, July, 1950.
- (27) McSkimin, H. J., "Measurement of Elastic Constants at Low Temperatures by Means of Ultrasonic Waves -- Data for Silicon and Germanium Single Crystals, and for Fused Silica," *J. Appl. Phys.*, vol. 24, pp. 988-997, August, 1953.
- (28) Merkulov, L. G., "Modern Ultrasonic Inspection," *Materials Research*, vol. 1, pp. 98-106, July, 1962.
- (29) McSkimin, H. J., "Pulse Superposition Method for Measuring Ultrasonic Wave Velocities in Solids," *J. Acoust. Soc. Am.*, vol. 33, pp. 12-16, January, 1961.
- (30) Sullivan, P. F., "Bonding Methods and a Bonding Clamp for Ultrasonic Measurements," *J. Acoust. Soc. Am.*, vol. 34, pp. 1879-1882, December, 1962.
- (31) Hastings, C. H., LoPilato, S. A., and L. C. Lynnworth, "Ultrasonic Inspection of Reinforced Plastics and Resin-Ceramic Composites," *Non-Destructive Testing*, vol. 19, pp. 340-346, September-October, 1961.

- (32) Handbook of Chemistry and Physics, 44th ed., The Chemical Rubber Publishing Company, Cleveland, Ohio, 1962.
- (33) Kolsky, H., Stress Waves in Solids, Oxford University Press, London, 1953.
- (34) Tu, L. Y., Brennan, J. N., and J. A. Sauer, "Dispersion of Ultrasonic Pulse Velocity in Cylindrical Rods," J. Acoust. Soc. Am., vol. 27, pp. 550-555, May, 1955.
- (35) Lindsay, Robert Bruce, Mechanical Radiation, McGraw-Hill Book Co., New York, 1960.
- (36) Hand, Walter, "Testing Reinforced Plastics with Ultrasonics," Plastics Technology, vol. 8, pp. 35-38, February, 1962.